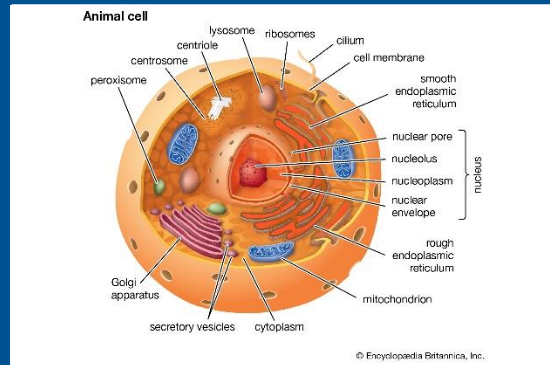
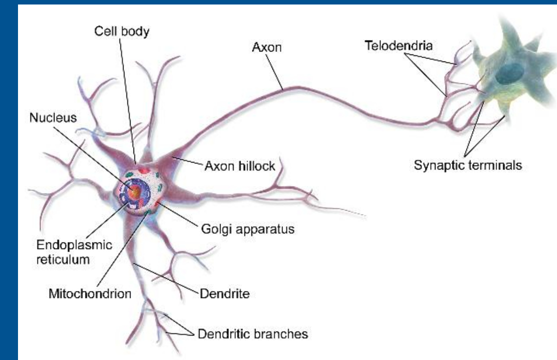
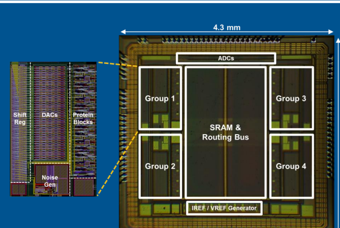
Cell-Inspired Supercomputing Chips

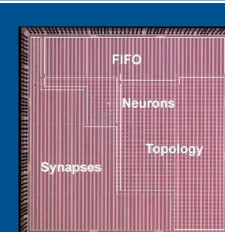
- Cytomorphic & Neuromorphic Approach -

Jaewook Kim

Post-silicon Semiconductor Institute
Korea Institute of Science and Technology (KIST)

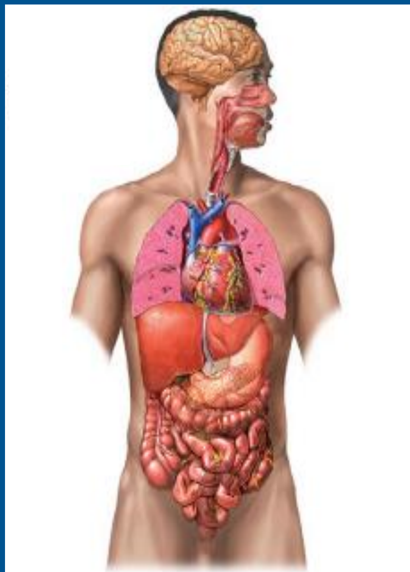
25 Feb 2021

<table>
<tr><th></th><th>Cellular Computation</th><th>Neural Computation</th></tr>
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>1. Basic computational unit device</td><td>A gene</td><td>A neuron</td></tr>
<tr><td>2. Discrete symbolic digital output of device</td><td>An mRNA transcript</td><td>A spike</td></tr>
<tr><td>3. Connection weighting</td><td>K_d and transcription-factor binding</td><td>Synaptic weight</td></tr>
<tr><td>4. Kinds of connections</td><td>Activatory and repressory</td><td>Excitatory and inhibitory</td></tr>
<tr><td>5. Connections per node</td><td>~12</td><td>~6000</td></tr>
<tr><td>6. Number of nodes</td><td>~30,000</td><td>~22 billion</td></tr>
<tr><td>Cell-inspired supercomputing chips</td><td>

Cytomorphic chip</td><td>

Neuromorphic chip</td></tr>
</table>

Can we fully simulate the human body?



Disease modeling
Drug testing

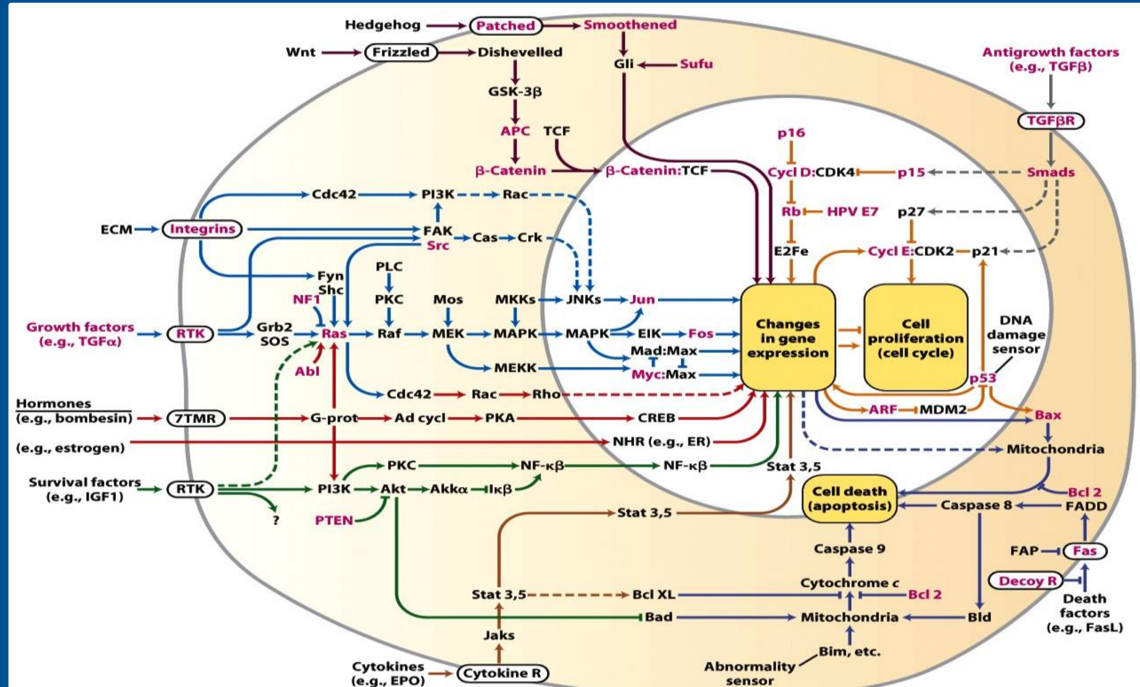


Figure 25-15
Molecular Cell Biology, Sixth Edition
© 2008 W. H. Freeman and Company

Signal pathways in cancer cells

TECHNOLOGY

Skip the Humans: Drug Discovery by Simulating Cells

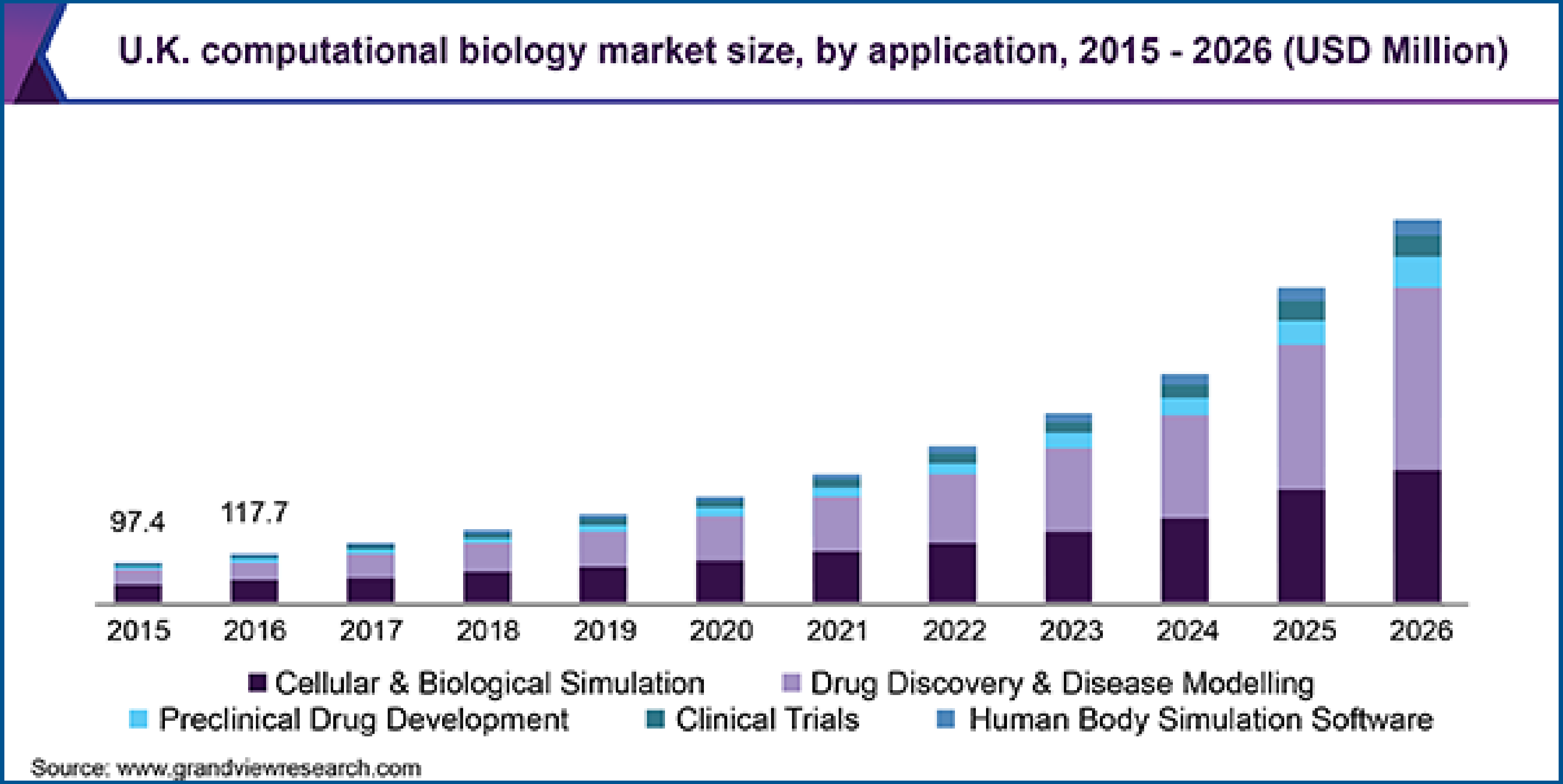
Virtual clinical trials would combine big data and computer simulation.

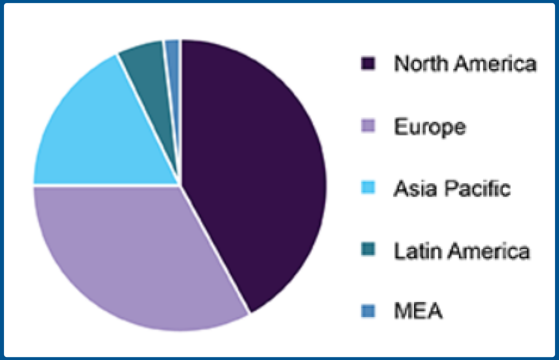
ADRIENNE LAFRANCE MAY 30, 2014

Animal testing outperformed by computer models

10 JUL 2018 BIOINFORMATICS & COMPUTATIONAL BIOLOGY

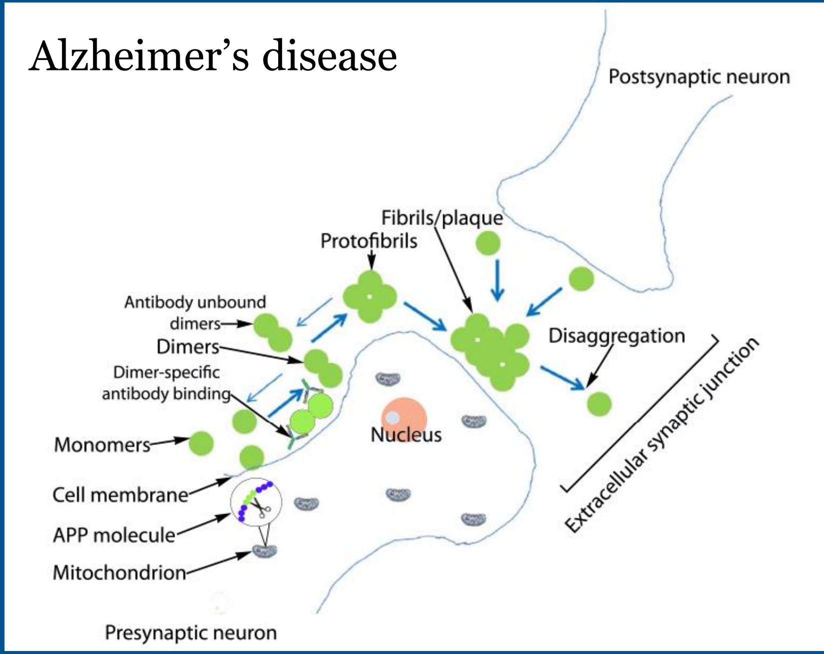
Market Size of Computational Biology

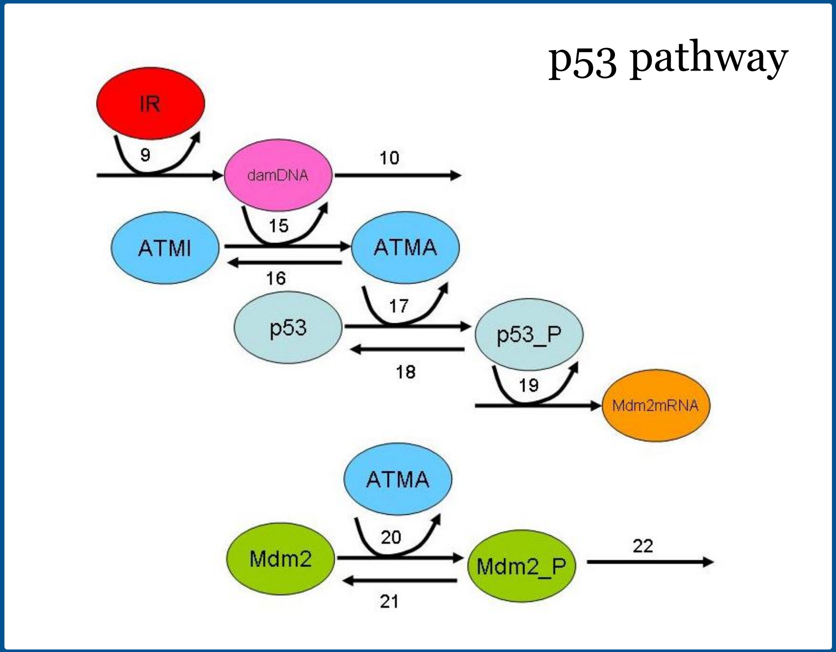


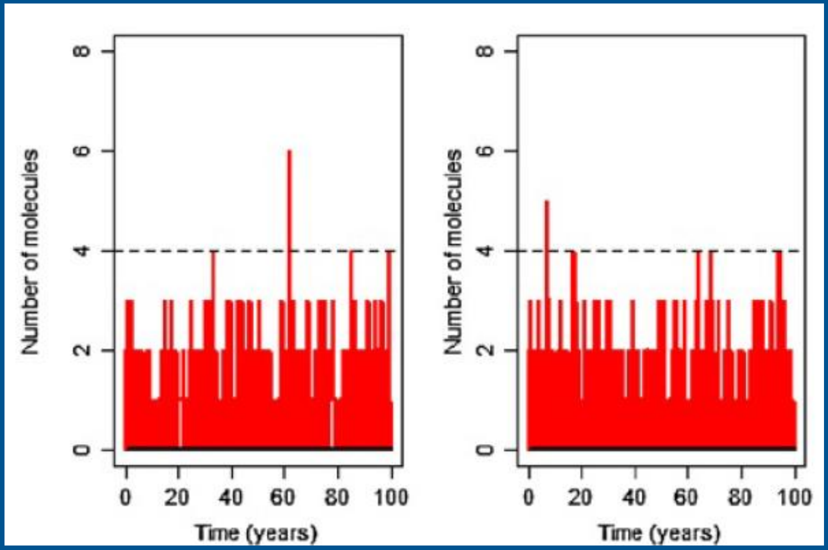


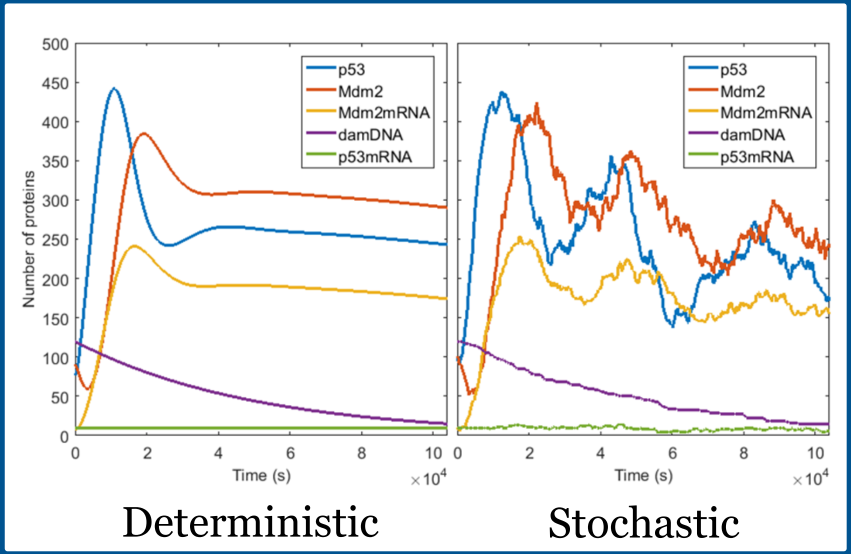
- USD 2.9 billion in 2018
- CAGR of 21.5% over the forecast period
- North America > Europe > Asia Pacific

Importance of Stochastic Simulation

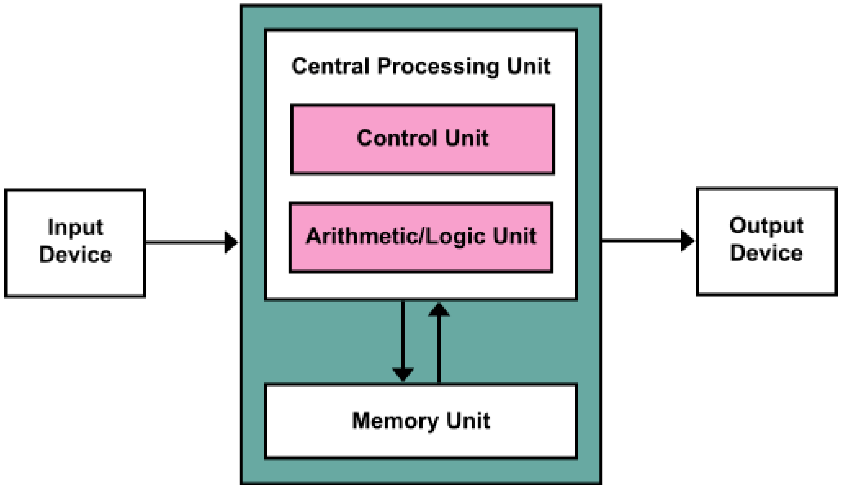








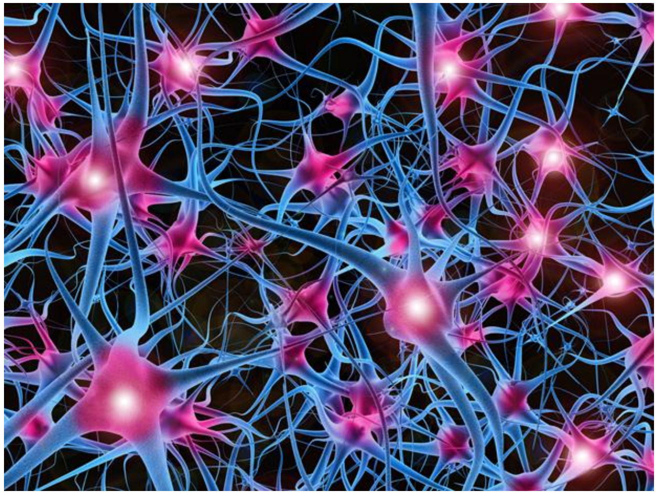
Problem of software simulation



Von-Neuman architecture

Serial, Deterministic

≠



Biological system

Parallel, Stochastic

E. Coli simulation : **12 years** ➔ **Long simulation time**

- 10^{14} reactions in one cell cycle
- 0.25million reactions/s
- Next reaction method (simplified model)

M. Schwehm. Fast stochastic simulation of metabolic networks. Proceedings of German Conference on Bioinformatics, 2001

Previous Works : GPU

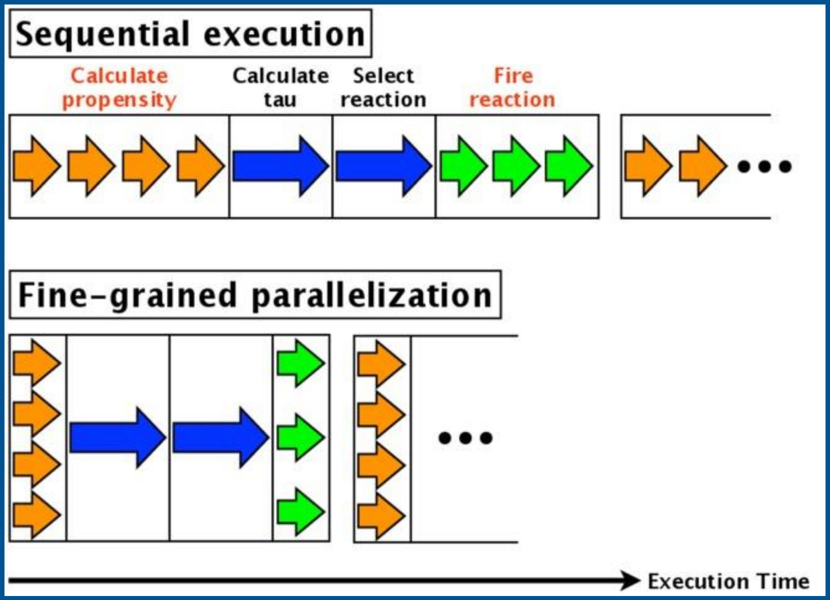


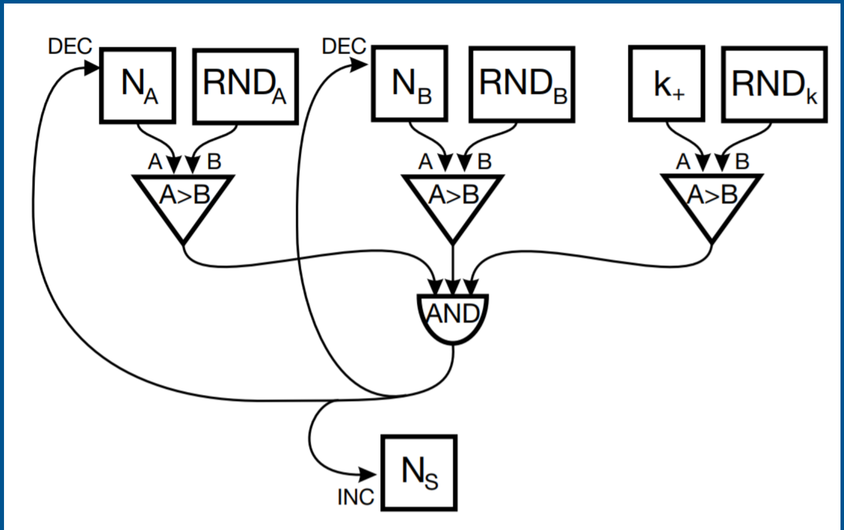
Table 5 | Execution times of 10,240 realizations with various sizes of model.

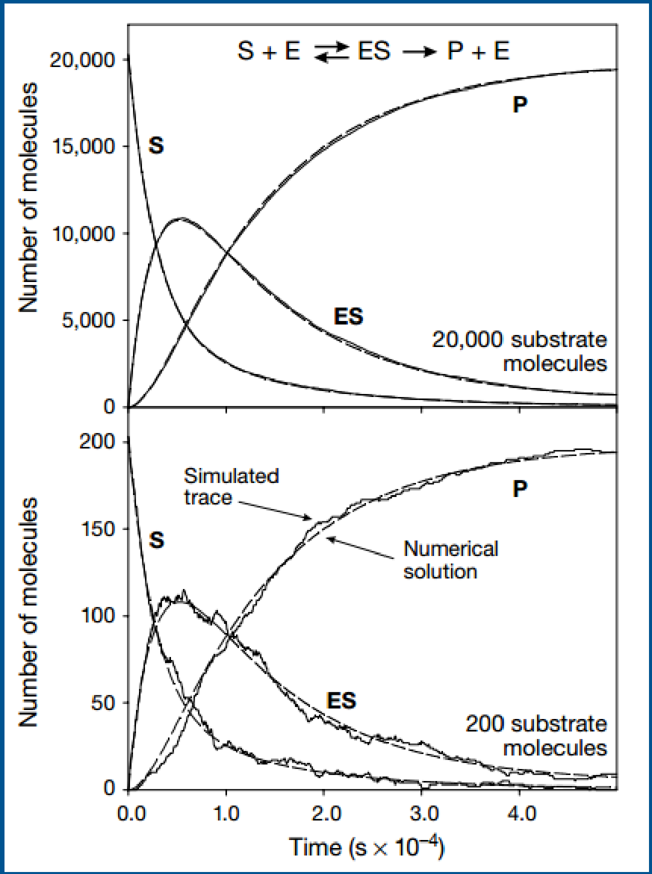
Number of reactions (model size)	Execution time (s)		CPU/GPU
	CPU	GPU	
8	58	0.45	128.89
16	70	0.59	118.64
32	98	0.85	115.29
64	142	1.54	92.21
128	237	2.88	82.29
256	406	5.52	73.55

- Only certain tasks can be processed in parallel
- As model size grows, simulation time grows
- 1-2 orders of magnitude speedup for a given network

Roberts et al. Noise contributions in an inducible genetic switch: a whole-cell simulation study. *PLOS Computational Biology*, 2011.

Previous Works : Digital Hardware (FPGA)

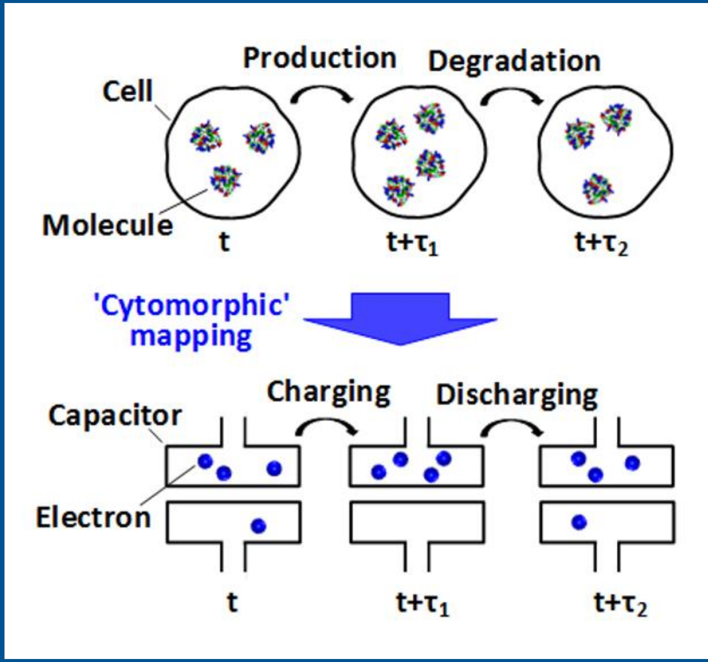


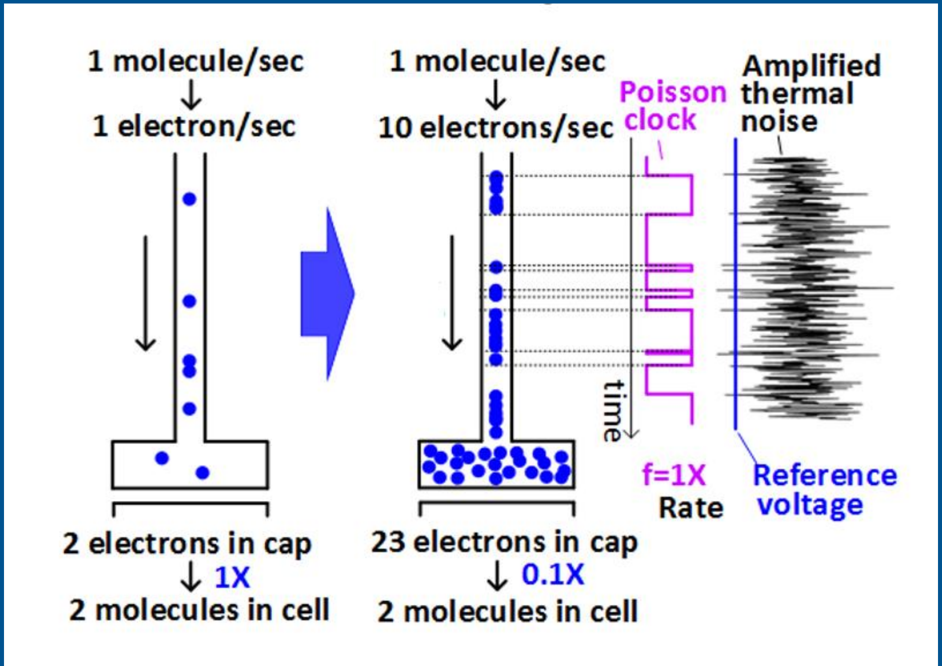


- Attempt to do parallel processing
- Discrete, same-size time steps
- An order of magnitude speedup over CPU

Lukasz Salwinski and David Eisenberg. In silico simulation of biological network dynamics. *Nature Biotechnology*, 2004.

The Approach of This Work





Cytomorphic mapping

\+ Continuous-time analog building-block circuits

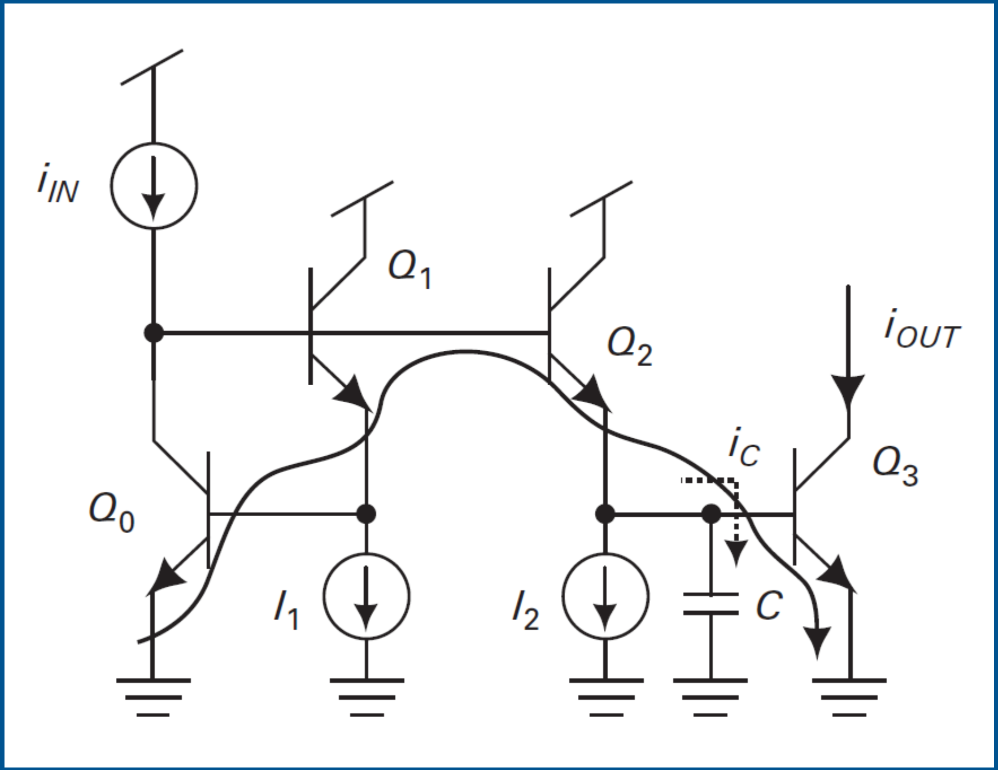
\+ Digital circuits for programmability

= Genuine **parallel** processing of stochastic biochemical simulation

Basis Function Circuit

$$E + S \underset{k_r}{\overset{k_f}{\rightleftharpoons}} ES$$

$$\frac{d[ES]}{dt} = k_f[E][S] - k_r[ES]$$



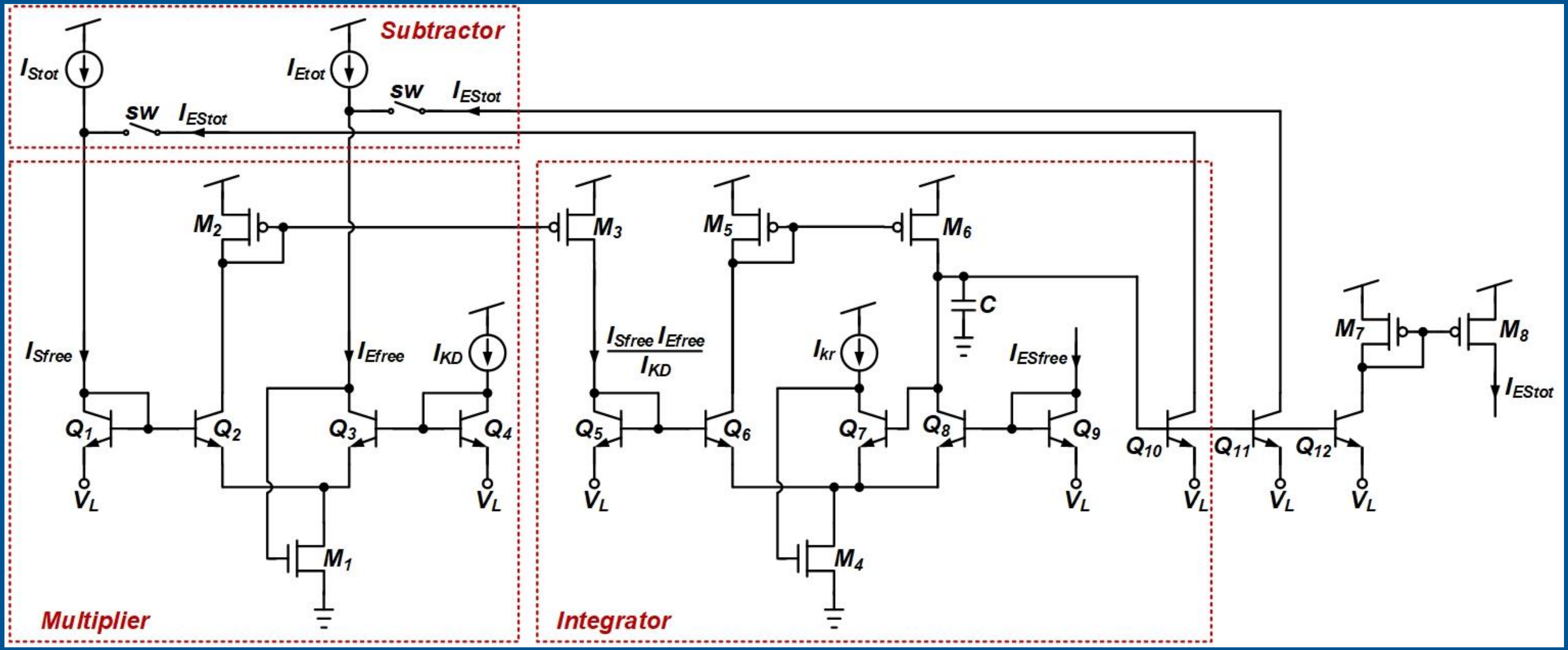
Dynamic translinear low-pass filter

$$i_{IN} I_1 = (I_2 + iC) i_{OUT}$$

$$i_C = \frac{C\phi_t}{\eta} \frac{1}{i_{OUT}} \frac{di_{OUT}}{dt}$$

$$\frac{di_{OUT}}{dt} = \left(\frac{i_{IN} I_1}{I_2} - i_{OUT}\right) \cdot \frac{I_2 \eta}{C\phi_t}$$

Basis Function Circuit

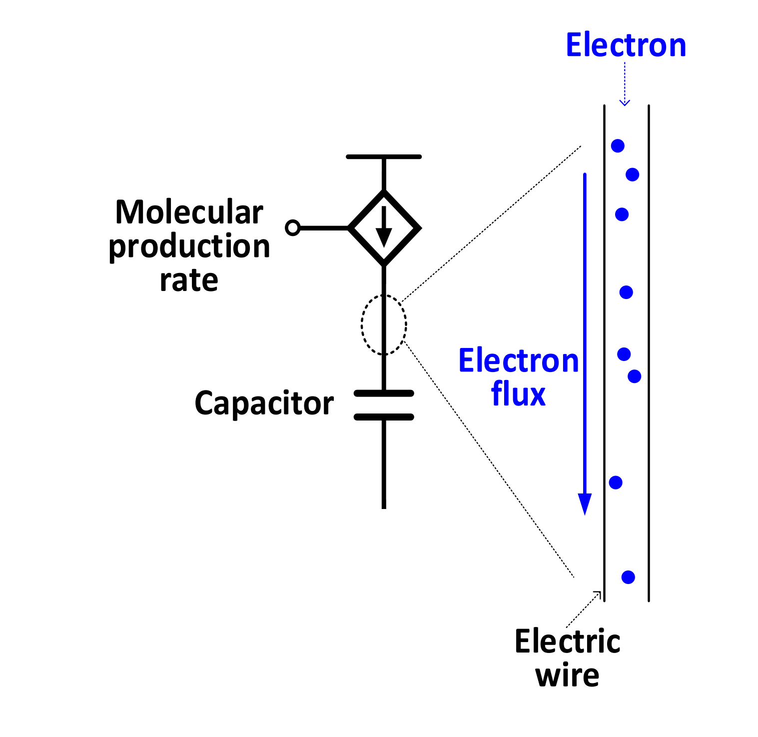


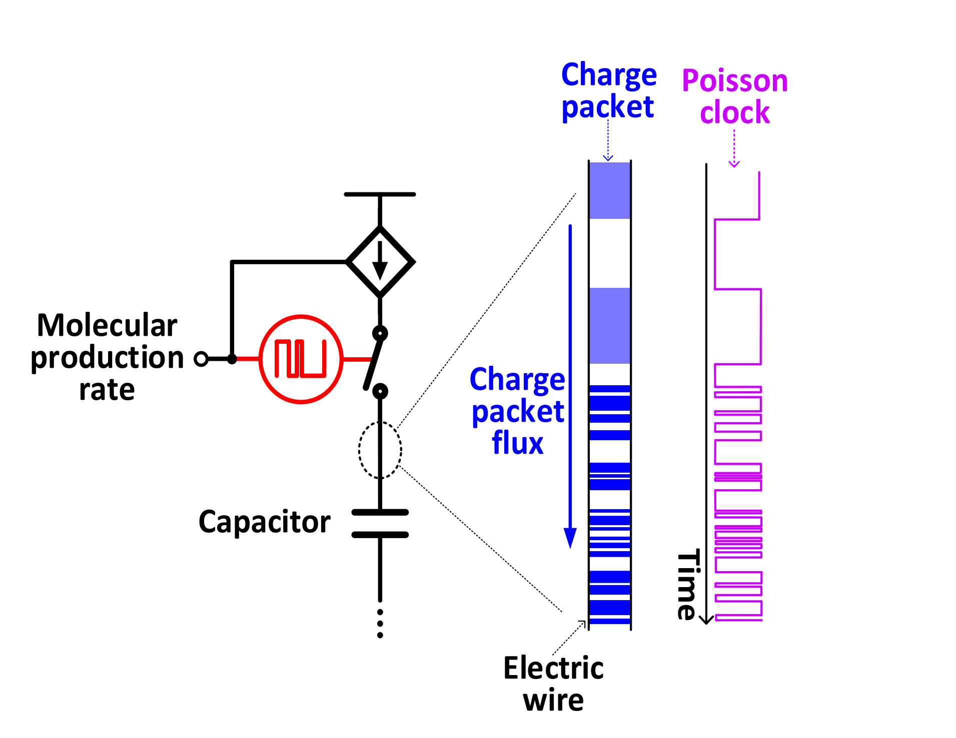
$$\frac{dI_{ES}}{dt} = \left(\frac{I_{Sfree} I_{Efree}}{I_{KD}} - I_{ESfree} \right) \cdot \frac{I_{kr}}{C\phi_t}$$

$$\frac{d[ES]}{dt} = k_f[E][S] - k_r[ES]$$

S. S. Woo, J. Kim, R. Sarpeshkar, "A cytomorphic chip for quantitative modeling of fundamental bio-molecular circuits." *IEEE TBCAS*, 2015

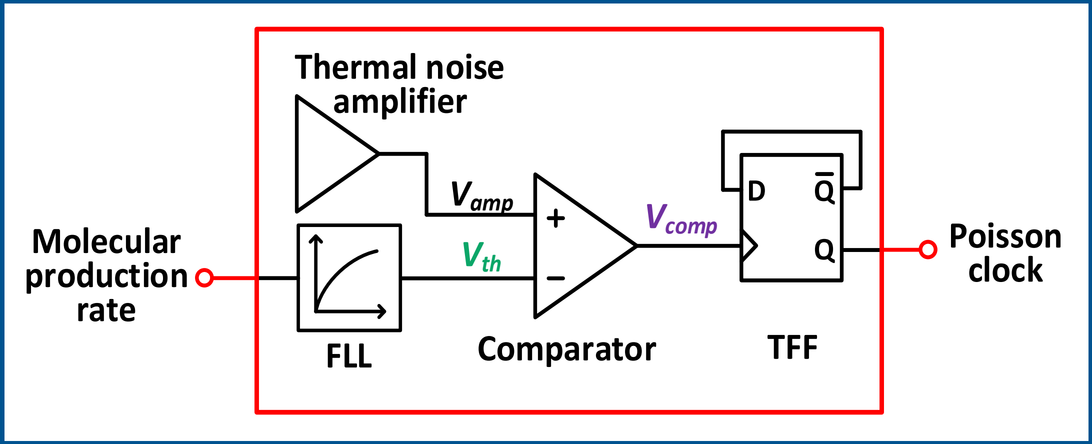
Stochastic Circuits



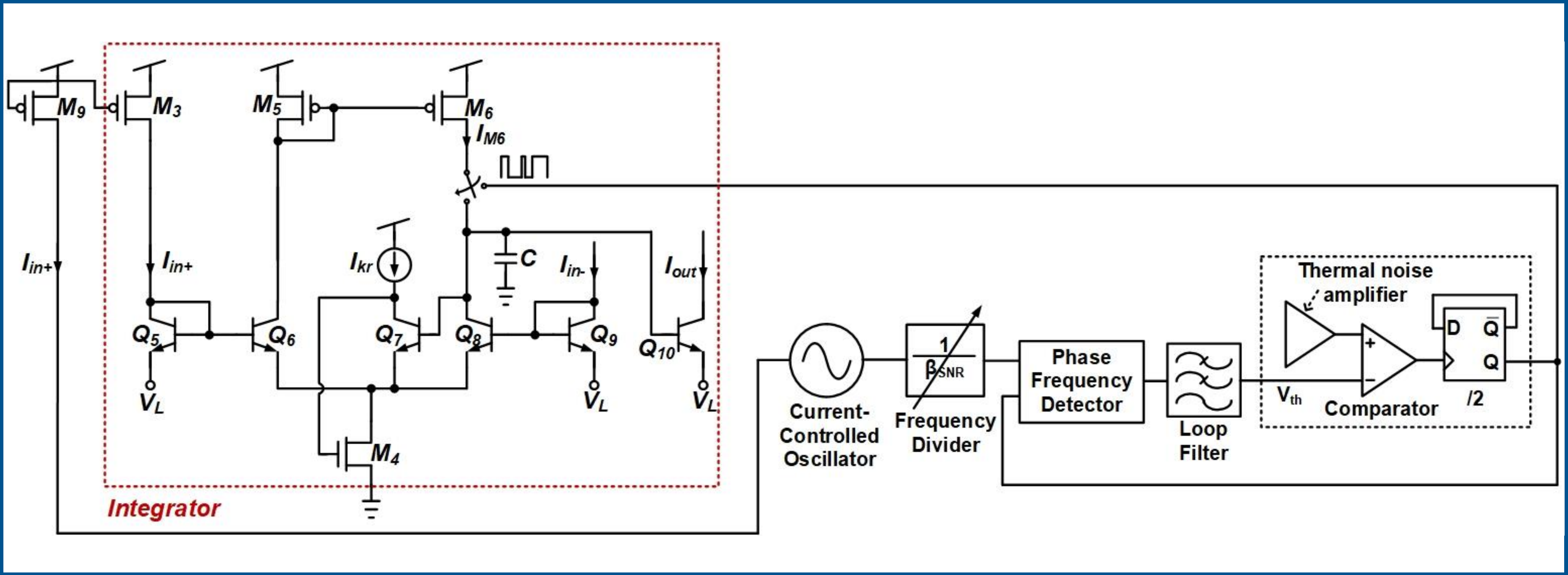


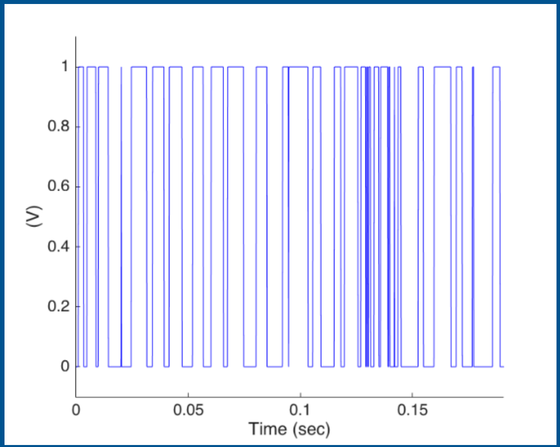
Non-ideal effect
- Parasitic capacitance
- Leakage current

Difficult to emulate
low # of molecules (<100)

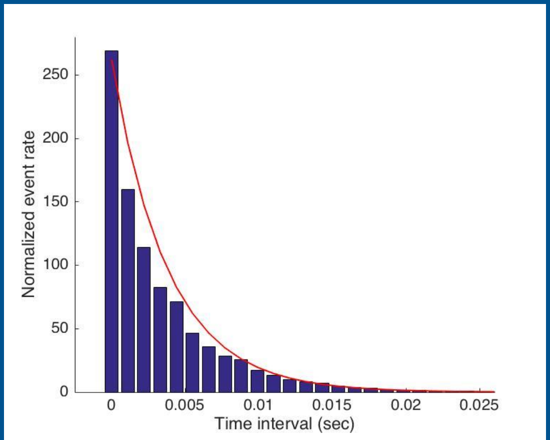


Stochastic Circuits

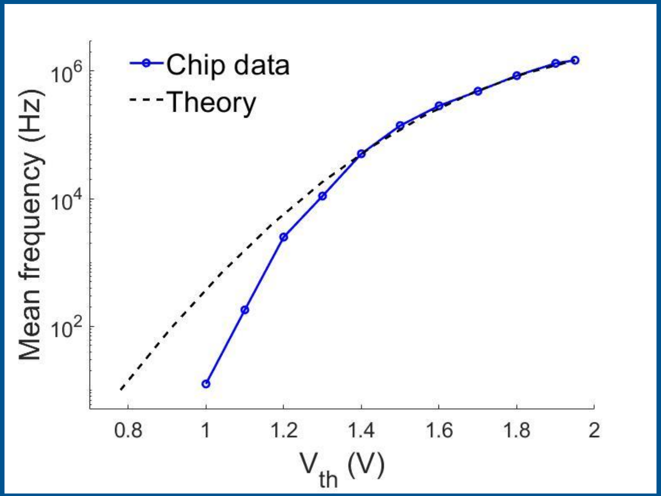




Measured waveform
(I_{in}=10nA)

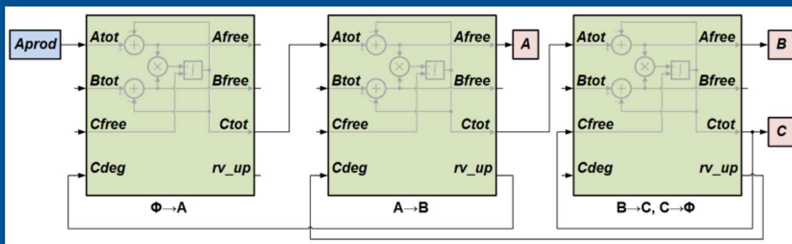


Time-interval histogram

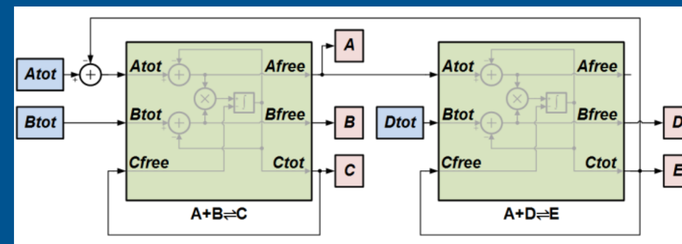


Any Topology Is Possible

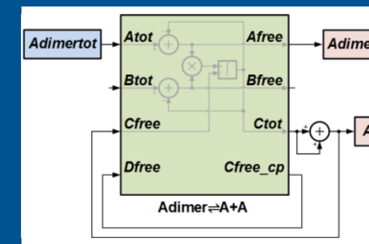
Cascade



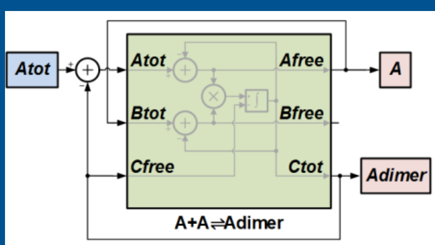
Fan-out



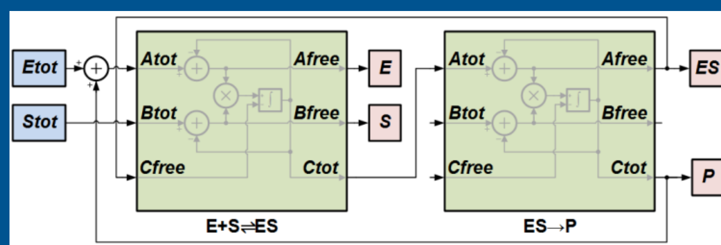
Monomerization



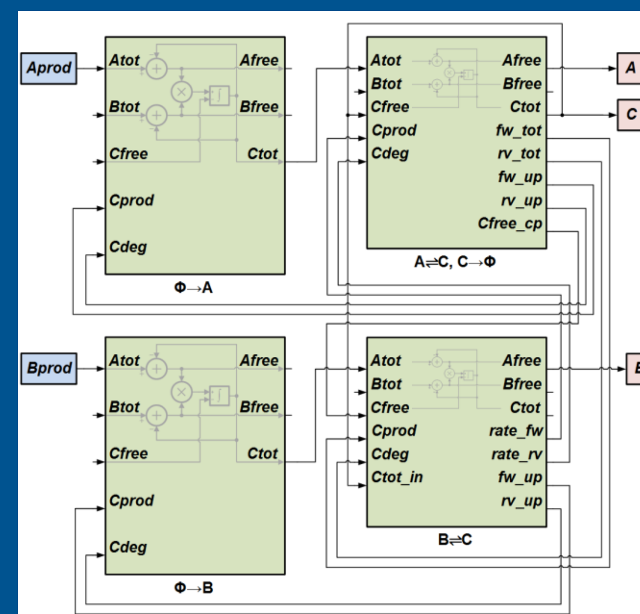
Dimerization



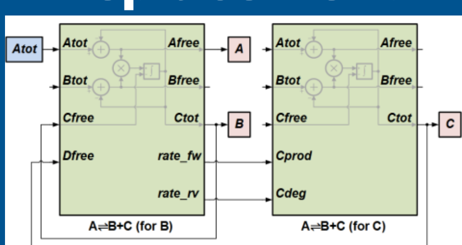
Michaelis-Menten



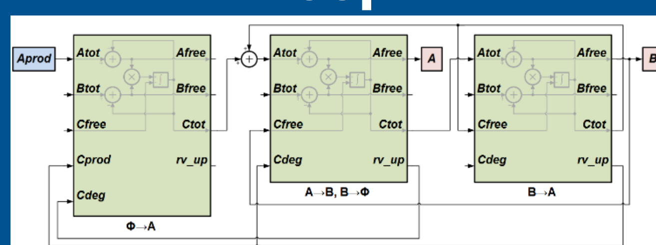
Fan-in



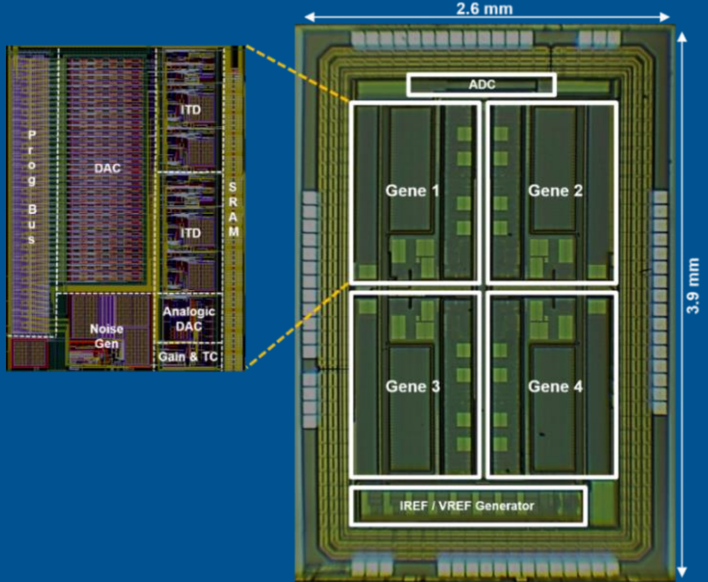
Replacement

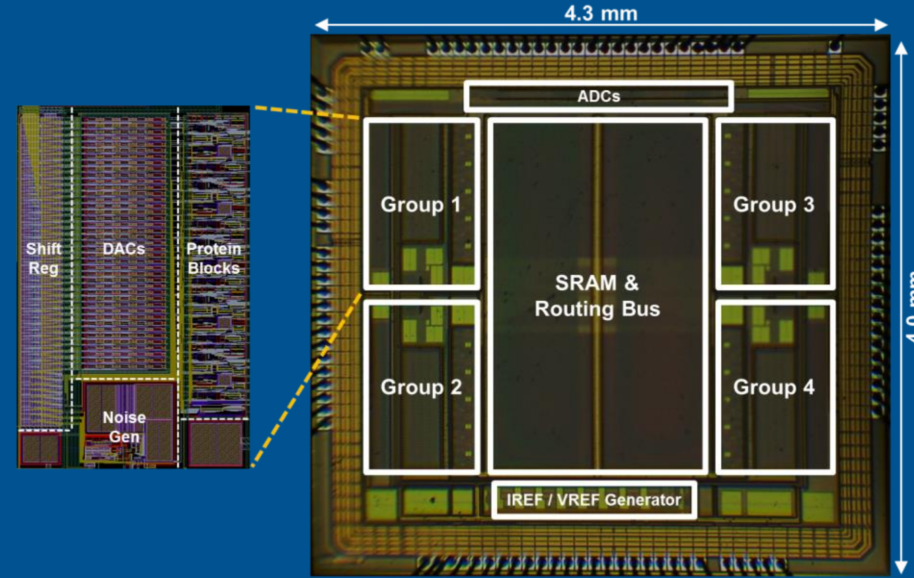


Loop



Gene and Protein Chips



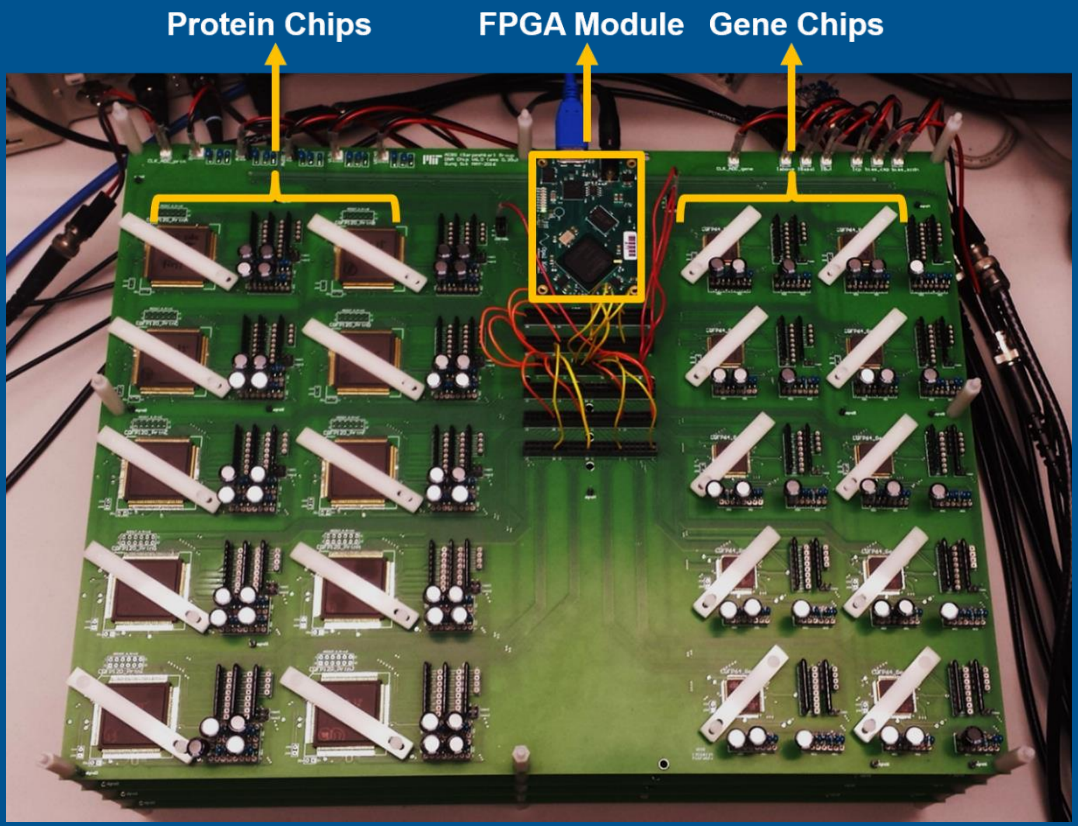


	The Gene Chip	**The Protein Chip**
Purpose	**DNA/RNA networks**	**Protein/metabolite networks**
Technology	AMS 0.35 µm BiCMOS	
Number of Reactions	80	60
Dynamic Range of Variables	100 dB	
Number of Noise Generators	4	
Number of ADCs	12	24
Number of DACs	160	164
Power Consumption	< 30 mW	
Programmability	**Connectivity, reaction rate, initial condition, Hill coefficient**	

J. Kim, et al. "Fast and Precise Simulation of Stochastic Biochemical Reactions with Amplified Thermal Noise in Transistor Chips," *IEEE TBCAS, 2018*

S. -S. Woo, et al. "A digitally programmable cytomorphic chip for simulation of arbitrary biochemical reaction networks." *IEEE TBCAS*, 2018

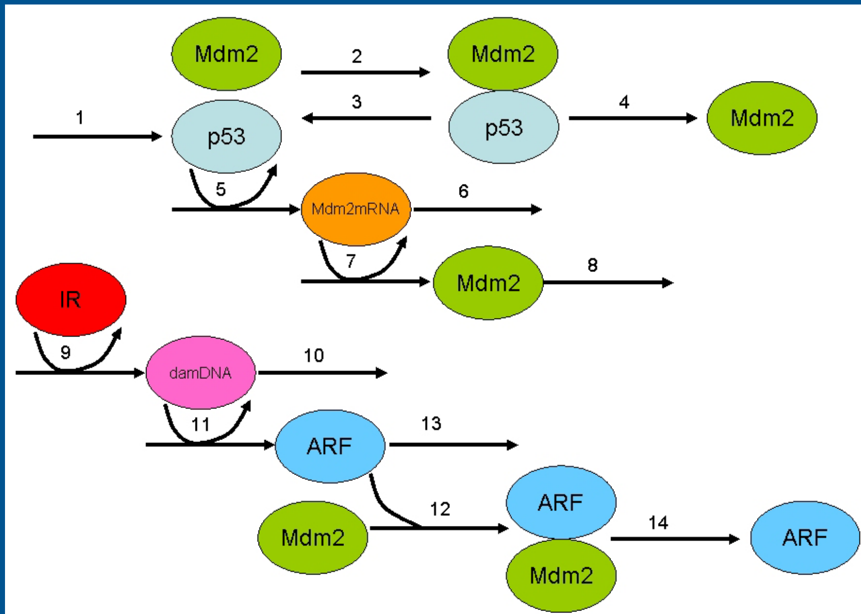
The Cytomorphic Board



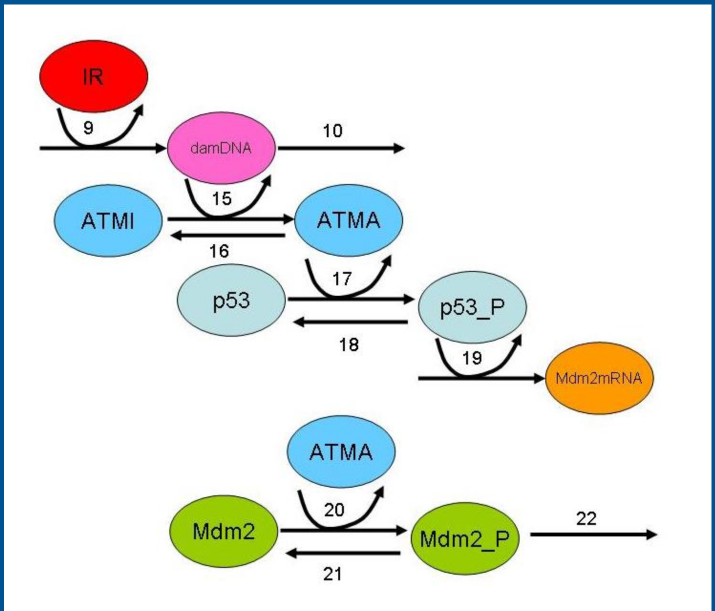
- Dimensions: 15.9 x 12.0 in^2
- Gene Chips: 10
- Protein Chips: 10
- FPGA Module: Opal Kelly's XEM6310 (features Xilinx Spartan-6)
- Computing Power: 1,400 Reactions

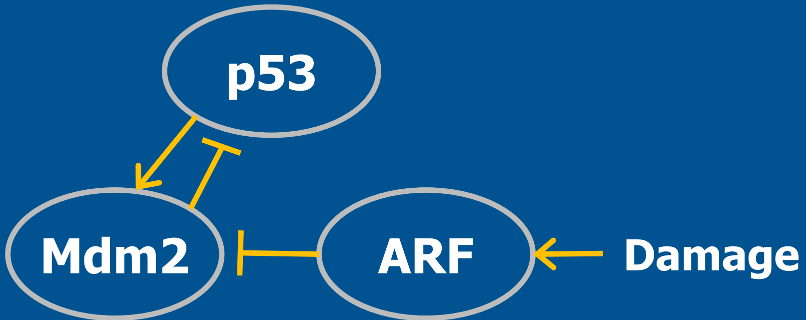
Test Results (p53 Signaling Pathway)

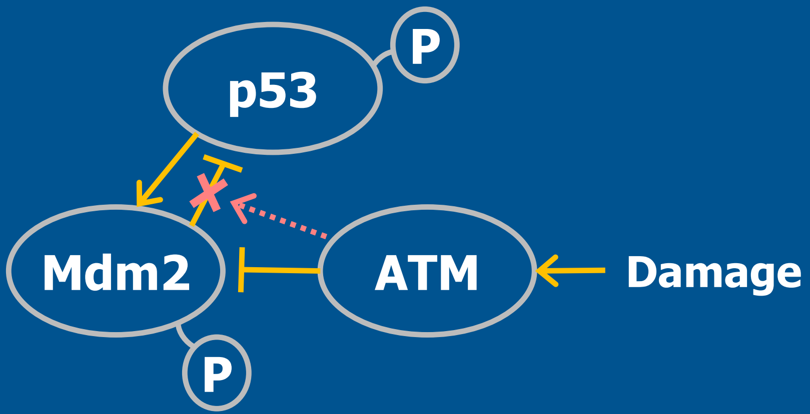
ARF Model



ATM Model

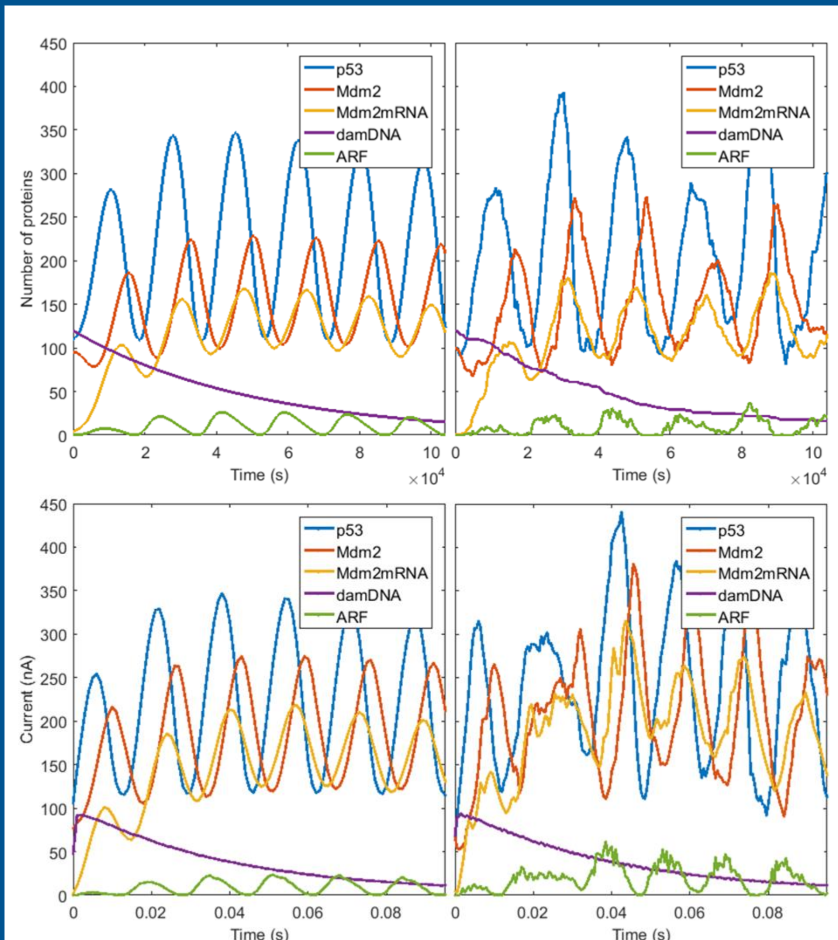




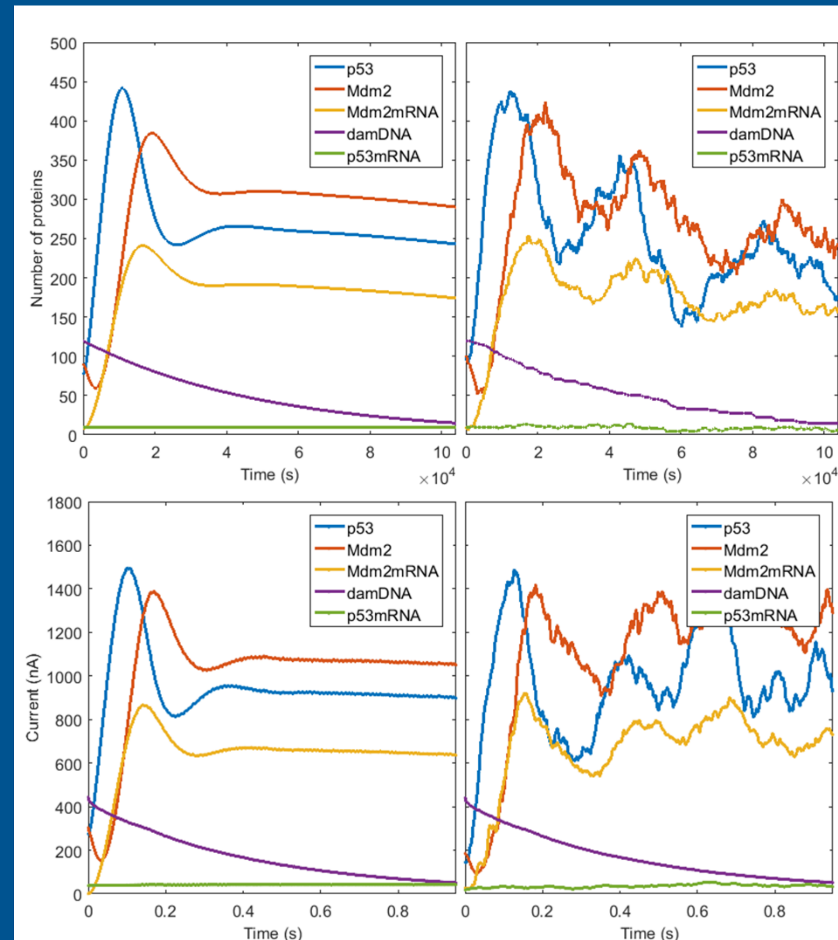


Test Results (p53 Signaling Pathway)

ARF Model



ATM Model



SW

Chip

Deterministic Stochastic Deterministic Stochastic

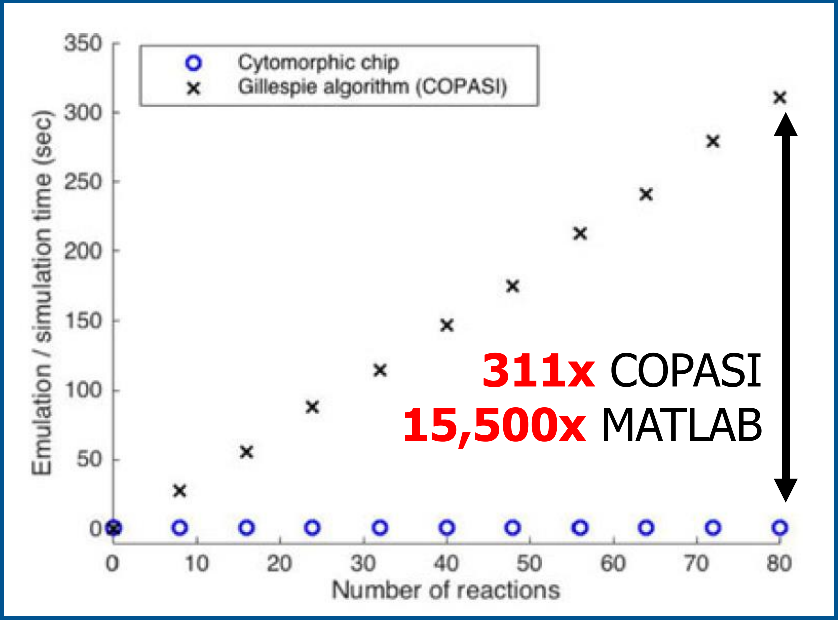
S. -S. Woo, J. Kim, and R. Sarpeshkar. "A digitally programmable cytomorphic chip for simulation of arbitrary biochemical reaction networks." *IEEE TBCAS*, 2018

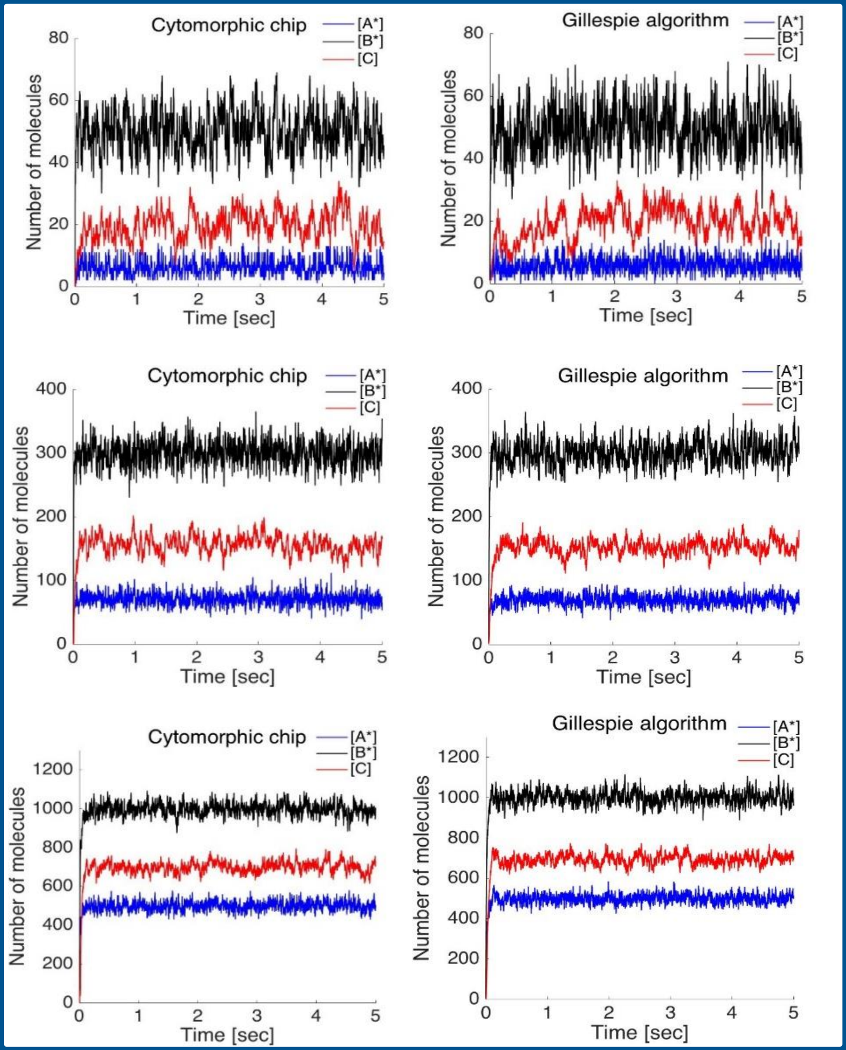
Speed vs. Scale

$$\phi \xrightarrow{K_{prodA}} A \xrightarrow{K_{degA}[A^*]} \phi$$

$$\phi \xrightarrow{K_{prodB}} B \xrightarrow{K_{degB}[B^*]} \phi$$

$$A + B \underset{K_{dissoc}[C]}{\overset{K_{assoc}[A^*][B^*]}{\rightleftarrows}} C$$

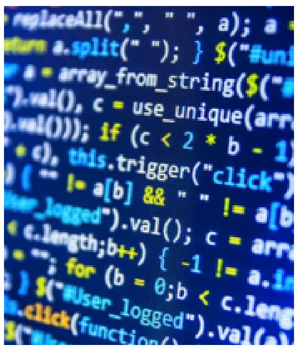




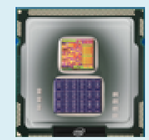
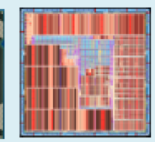
Chips Software

J. Kim, S.-S. Woo, and R. Sarpeshkar, "Fast and Precise Simulation of Stochastic Biochemical Reactions with Amplified Thermal Noise in Transistor Chips," *IEEE TBCAS, 2018*

Classification of Neuromorphic Systems

<table>
<tr><td>Software strategies</td></tr>
<tr><td>Deep neural networks</td></tr>
<tr><td>Deep learning
</td></tr>
</table>

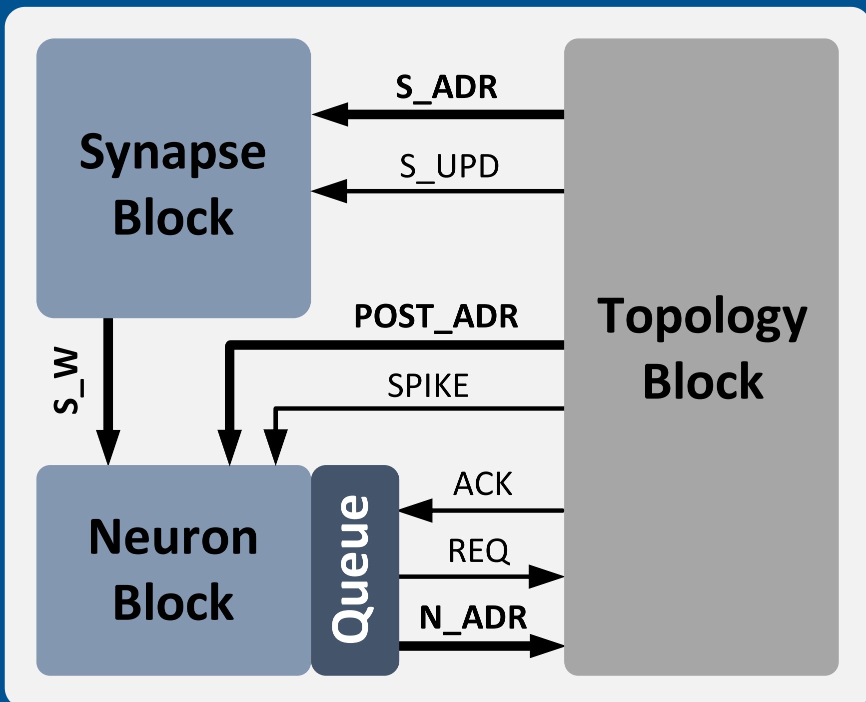
<table>
<tr><td colspan="5">Hardware strategies</td></tr>
<tr><td>Deep neural networks</td><td colspan="4">Spiking neural networks (SNN)</td></tr>
<tr><td rowspan="3">Deep learning accelerators based on GPU</td><td colspan="2">Training with the aid of computers</td><td colspan="2">Standalone training</td></tr>
<tr><td colspan="2">Synaptic weight storage</td><td colspan="2">Synaptic weight storage</td></tr>
<tr><td>SRAM

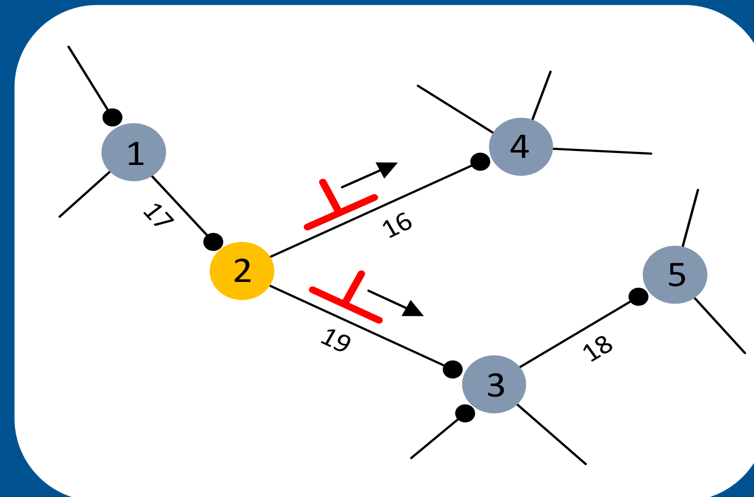
IBM TrueNorth (2014)</td><td>Emerging memories : RRAM</td><td>SRAM
 
Intel Loihi (2017) KIST Neo^{2}C (2018)</td><td>Emerging memories : RRAM</td></tr>
<tr><td colspan="3">Non-standalone neuromorphic systems</td><td colspan="2">Standalone</td></tr>
<tr><td colspan="3">Offline learning only</td><td colspan="2">Online learning</td></tr>
</table>

Difficulty →

← Technology readiness level

Architecture of a Neuromorphic Core

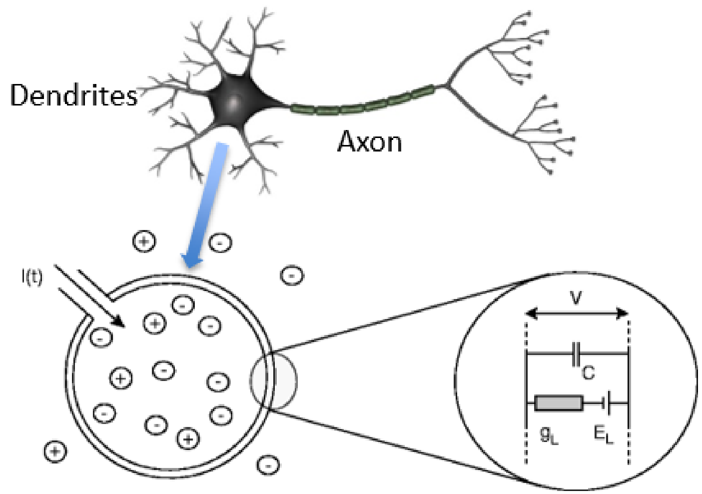


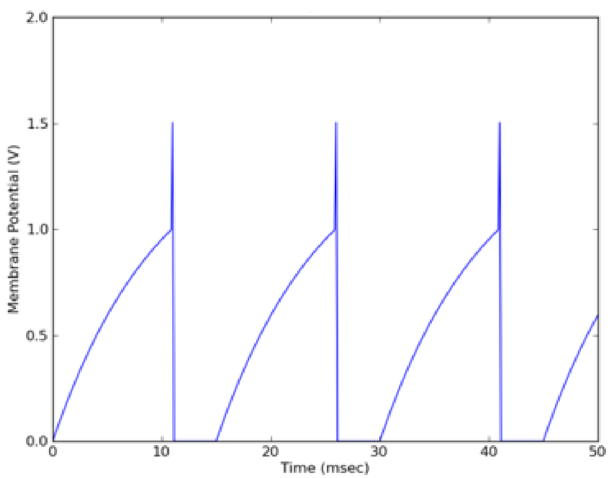


Topology Look-Up Table (LUT)

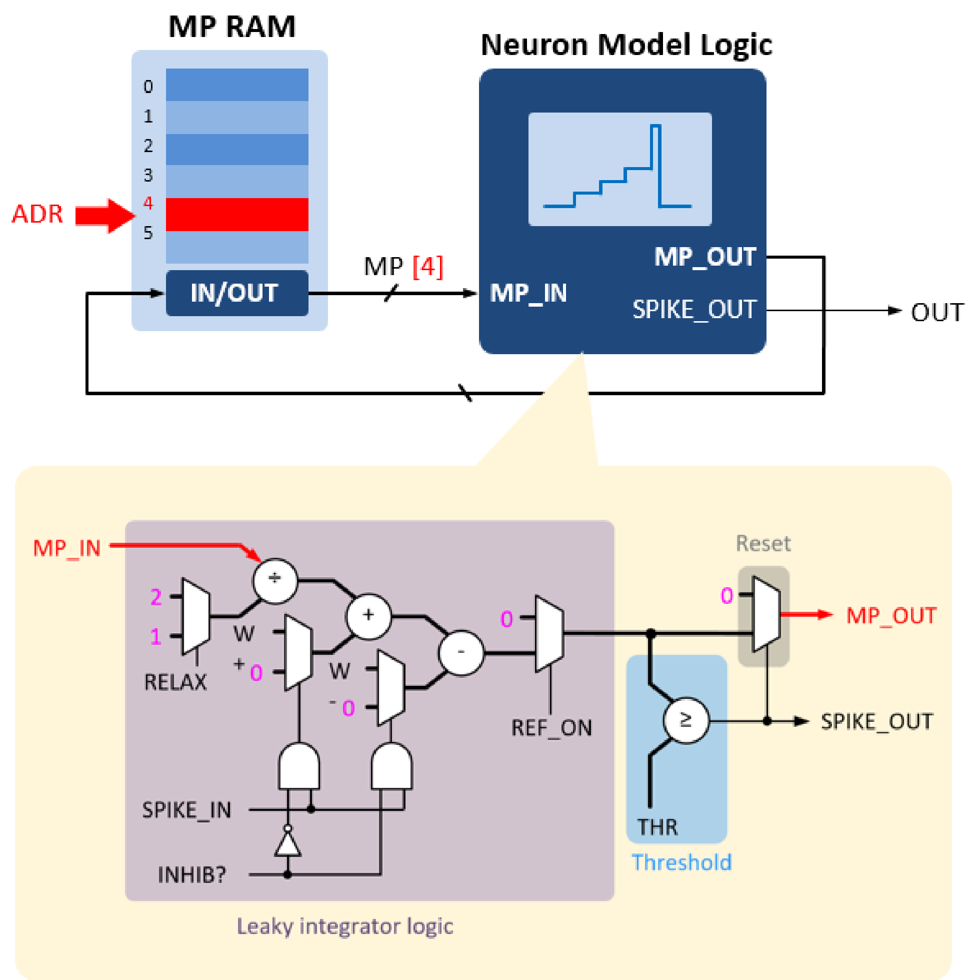
	PRE_ADR	POST_ADR
⋮		
16	2	4
17	1	2
18	3	5
19	2	3
⋮		

Leaky-Integrate and Fire (LIF) Neuron

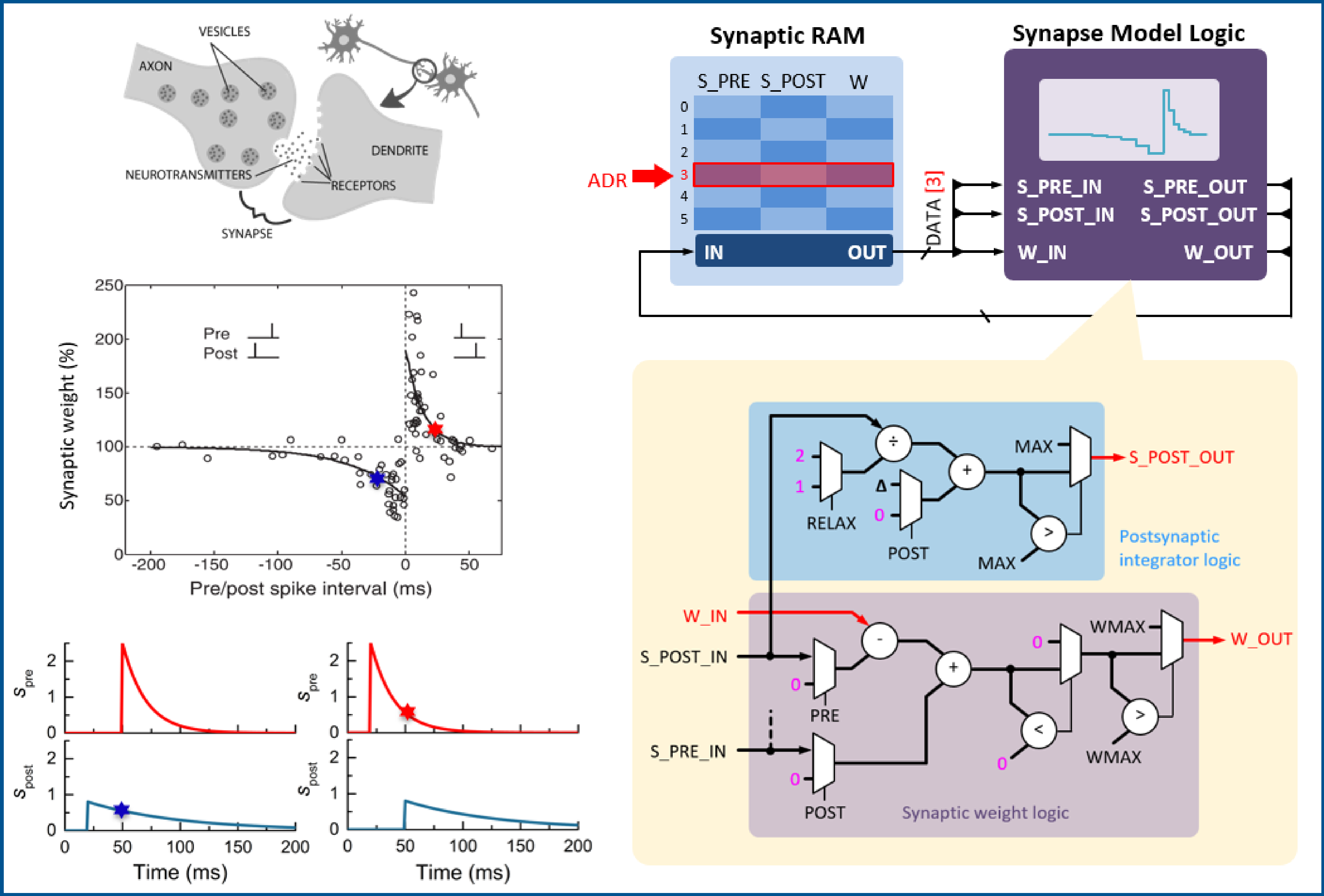




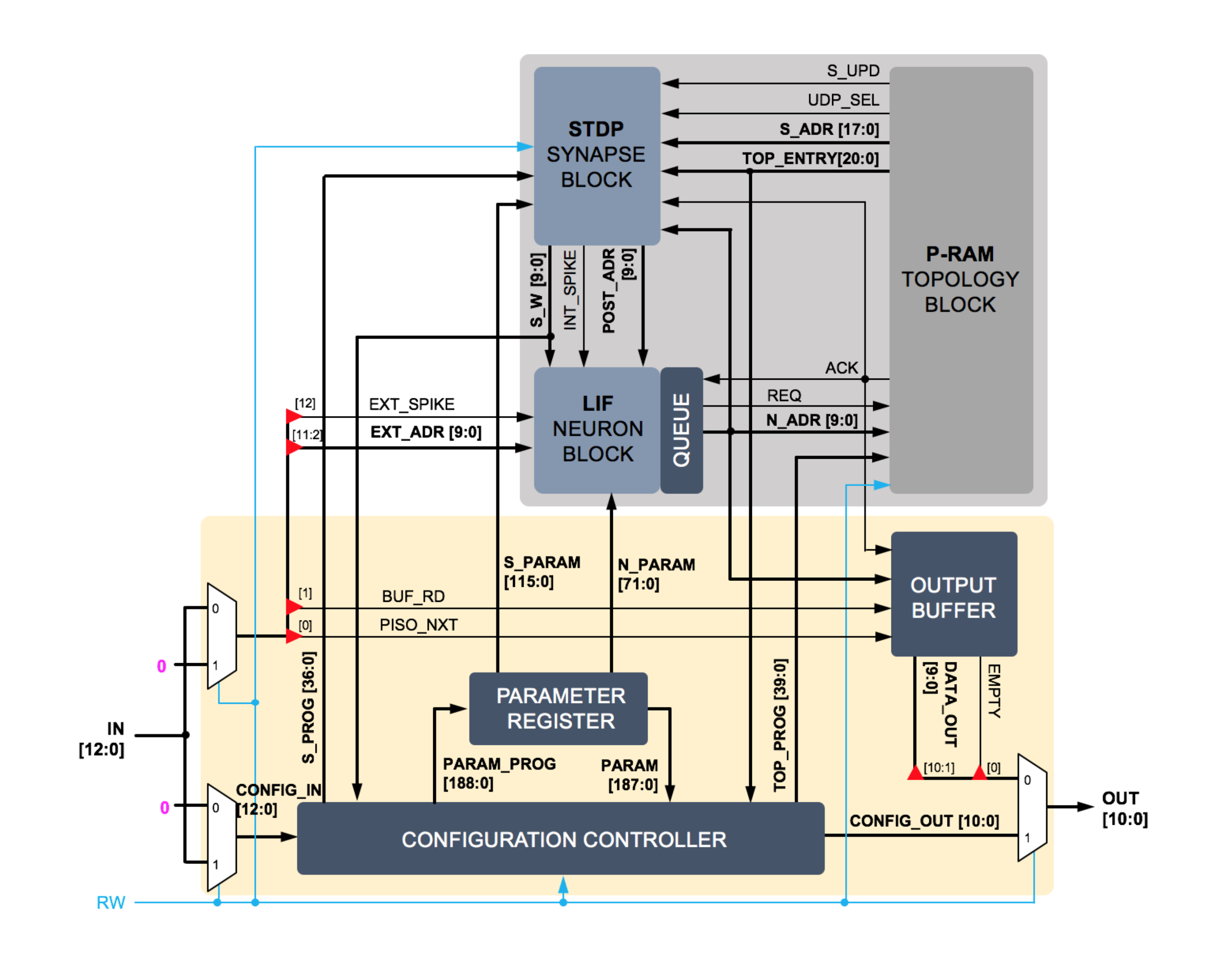
LIF model with refractory period



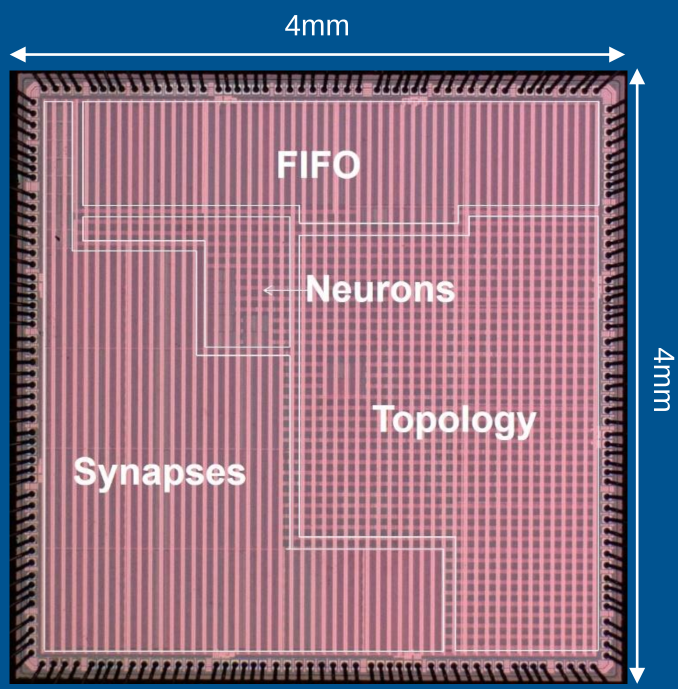
Spike-Timing Dependent Plasticity Synapse

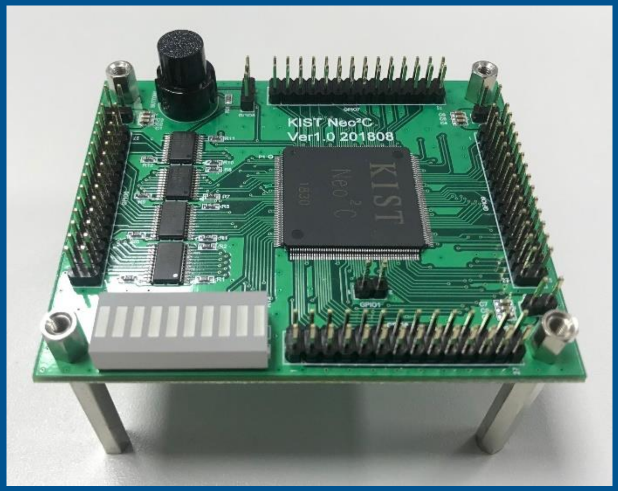


KIST Neo^{2}C neuromorphic chip



KIST Neo^{2}C neuromorphic chip

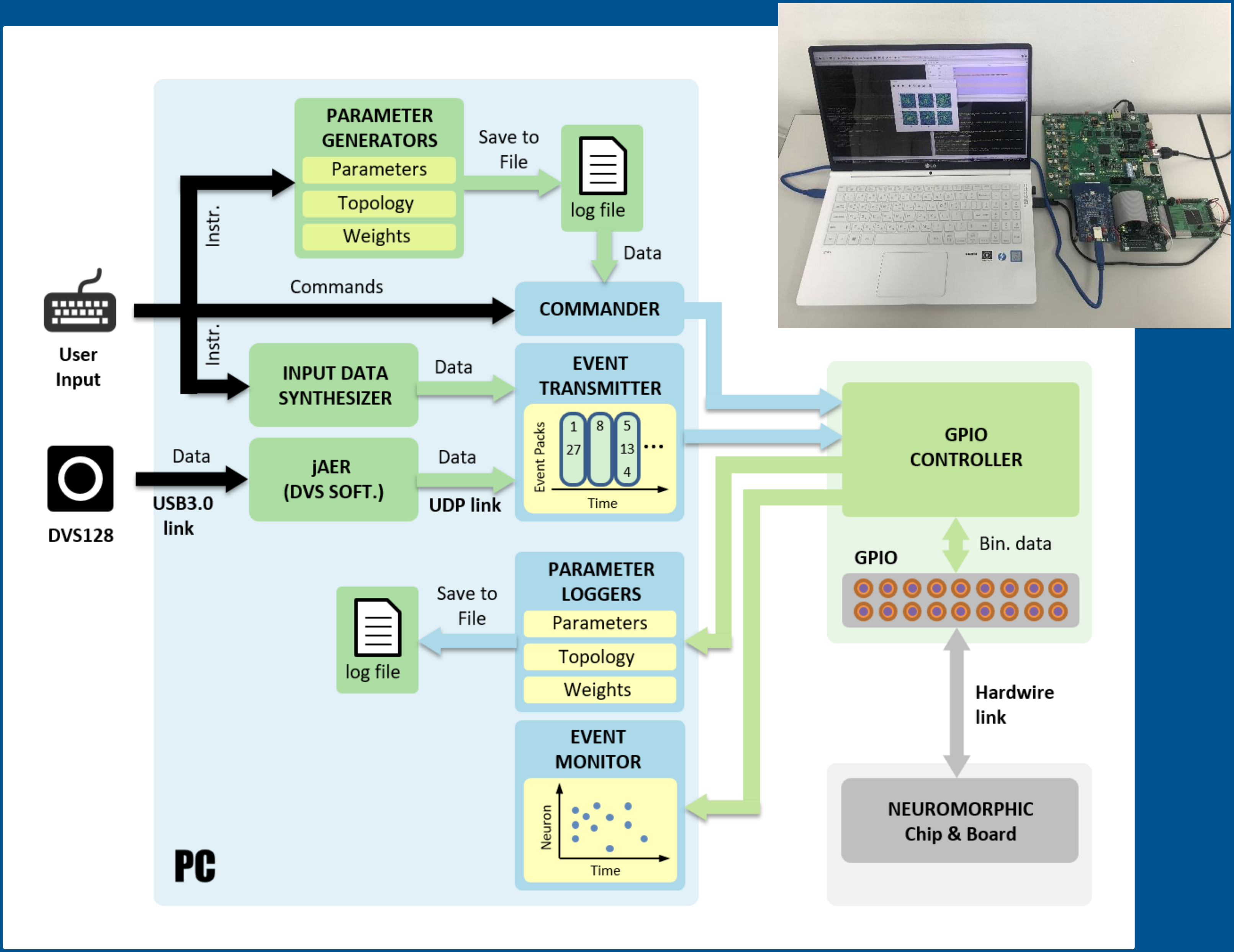


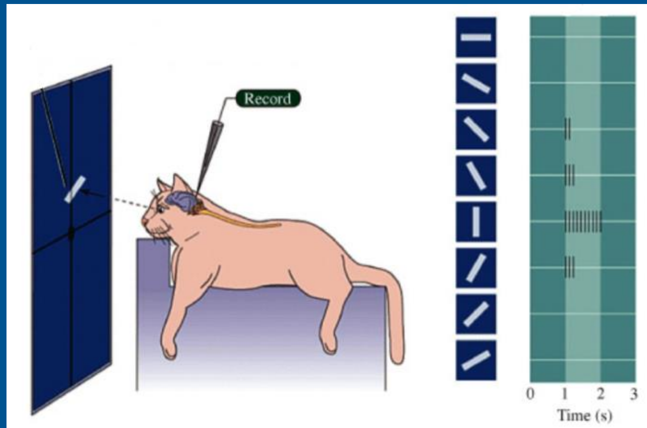


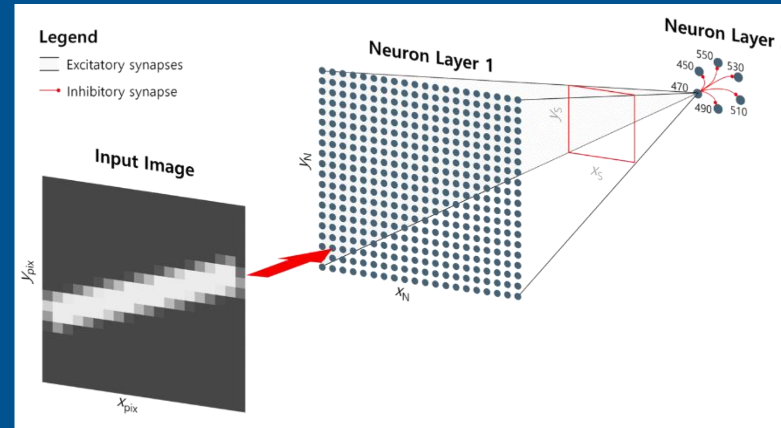
Parameters	KIST Neo^{2}C
Process & technology	55 nm CMOS
Area	16 mm^2
Number of neurons	1,024
Number of synapses	199,680
Number of cores	1
On-chip learning	Yes
Learning rule	STDP
Supply voltage	1 V
Clock frequency	100 MHz
Power consumption	56 mW

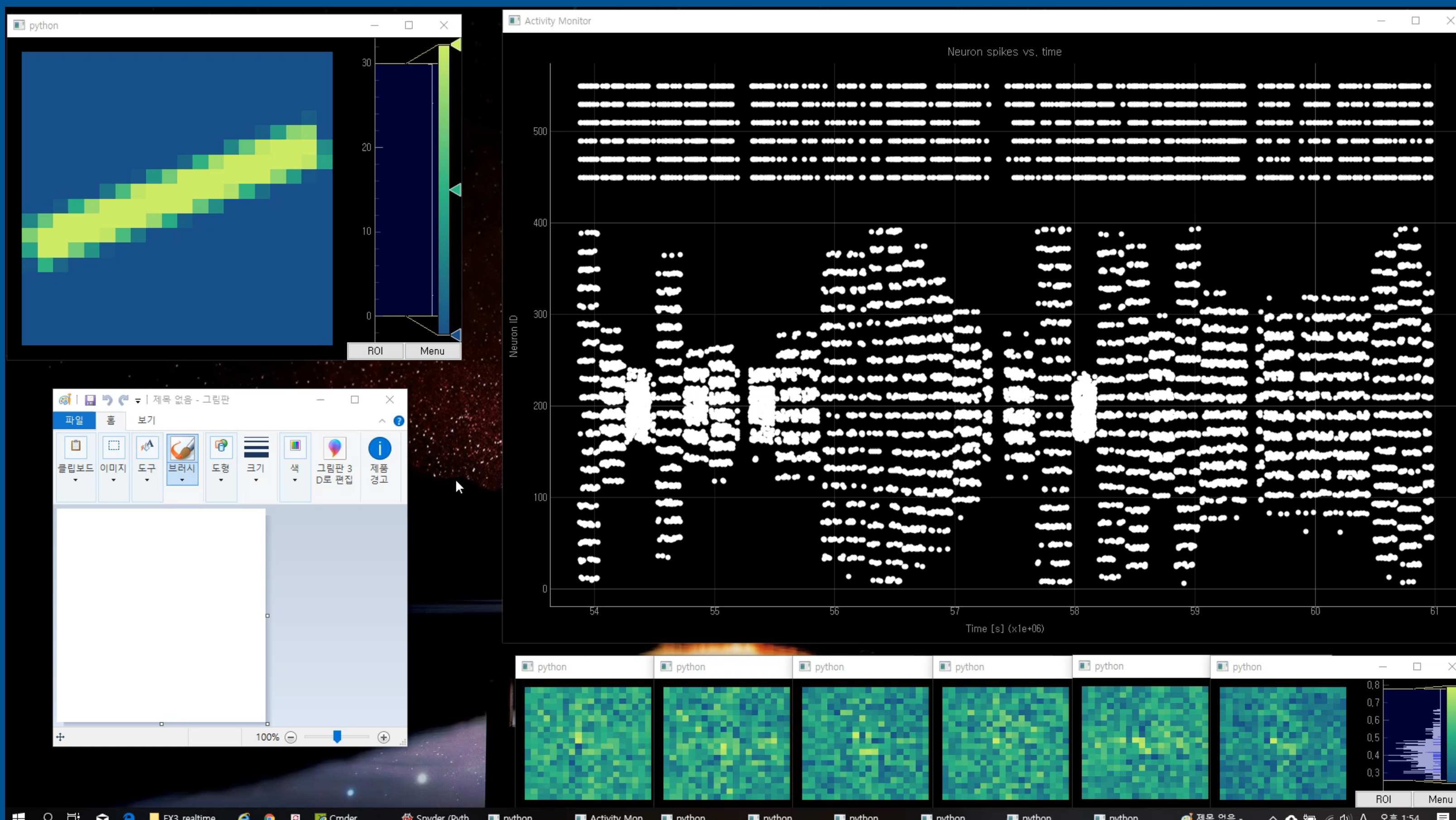
- **Fully reconfigurable spiking** neuromorphic system
- **On-chip, online, unsupervised** learning
- Learning rule: STDP with all-to-all spike interaction
- Fully digital implementation

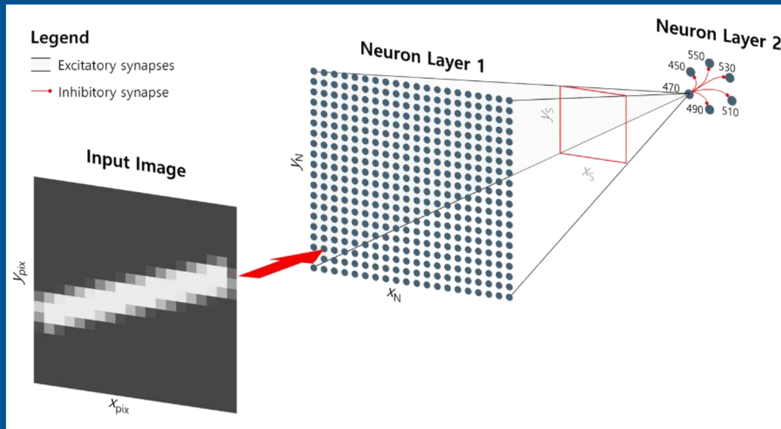
KIST Neo^{2}C neuromorphic system

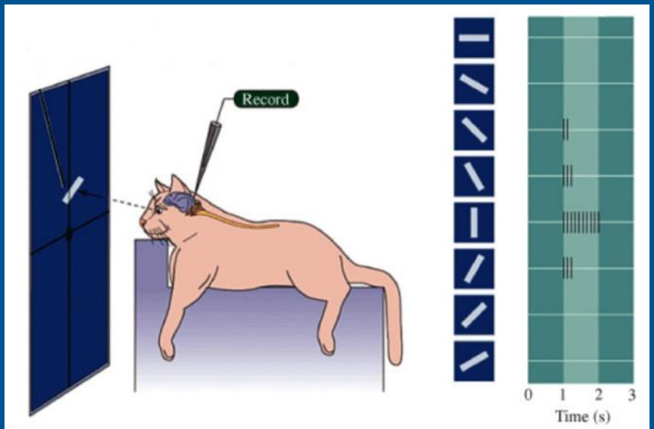


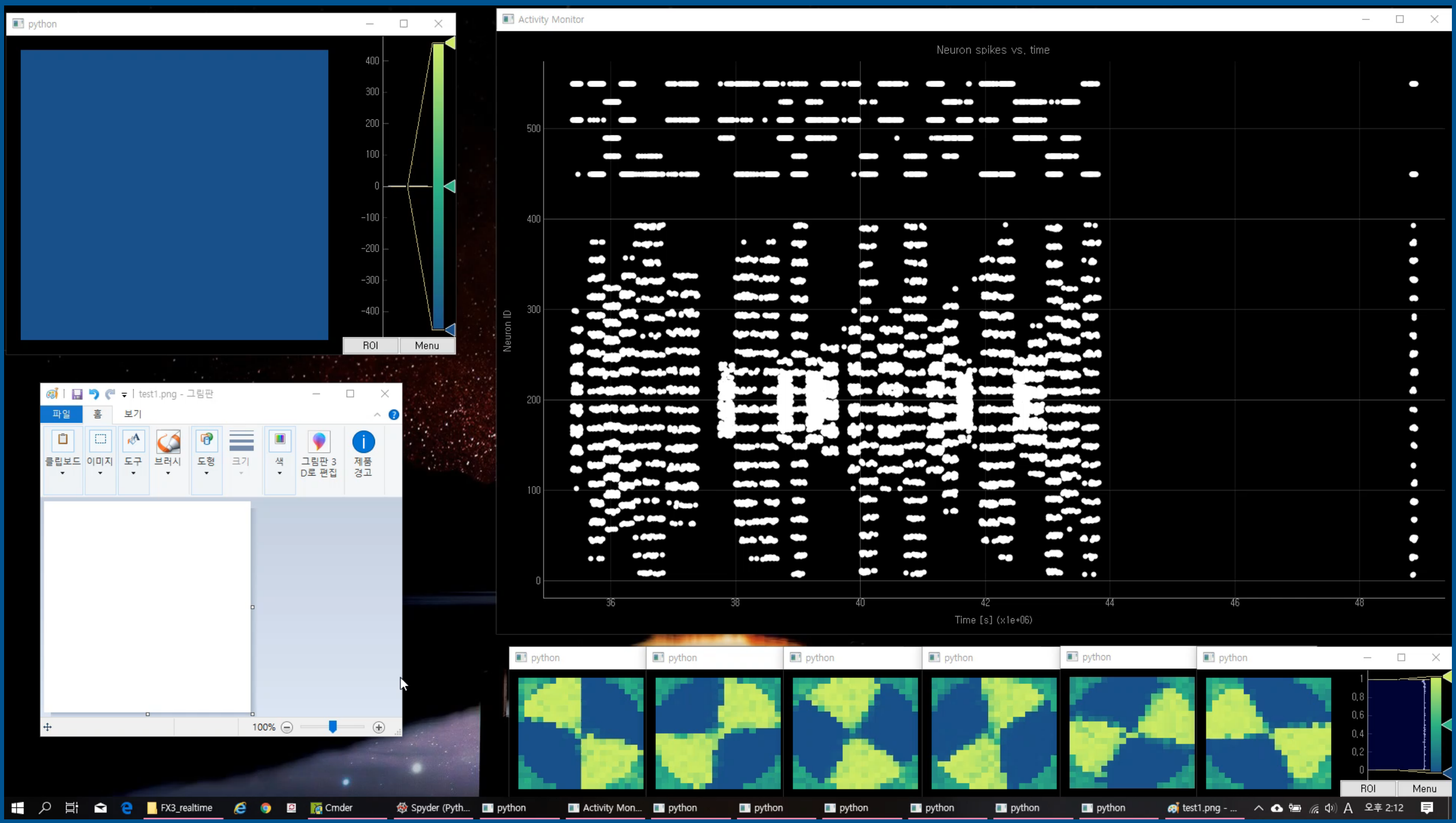

Record
0 1 2 3
Time (s)


Legend
Excitatory synapses
Inhibitory synapse
Input Image
Neuron Layer 1
Neuron Layer 2
550
450
530
470
490
510


python
30
20
10
0
ROI
Menu
Activity Monitor
Neuron spikes vs. time
Neuron ID
500
400
300
200
100
0
54 55 56 57 58 59 60 61
Time [s] (x1e+06)
제목 없음 - 그림판
파일
홈
보기
클립보드
이미지
도구
브러시
도형
크기
색
그림판 3D로 편집
제품 경고
100%
python
0.8
0.7
0.6
0.5
0.4
0.3
ROI
Menu
FX3_realtime
Cmder
Spyder (Pyth...
python
Activity Mon...
python
python
python
python
python
python
제목 없음 - ...
오후 1:54


Legend
Excitatory synapses
Inhibitory synapse
Input Image
Neuron Layer 1
Neuron Layer 2
550
450
530
470
490
510


Record
0
1
2
3
Time (s)


python
ROI
Menu
Activity Monitor
Neuron spikes vs. time
Neuron ID
Time [s] (x1e+06)
test1.png - 그림판
파일
홈
보기
클립보드
이미지
도구
브러시
도형
크기
색
그림판 3D로 편집
제품 경고
100%

Acknowledgements

Cytomorphic chip project

- Dr. Sungsik Woo
- Prof. Rahul Sarpeshkar

Massachusetts Institute of Technology

Dartmouth

Neuromorphic chip project

- Dr. Vladimir Kornijcuk
- Prof. Dooseok Jeong
- Dr. Joonyoung Kwak
- Dr. Jongkil Park
- Dr. Joonyeon Chang

KIST
Korea Institute of Science and Technology

PSI
Post-silicon Semiconductor Institute

Thank you for your attention!